2.5 Model Strategy – Operational and 10,000 Year Models

For this 2000 HWDIR Exemption Petition Reissuance, modeling of injection at Lyondell Chemical Company, Channelview Plant, considers three time frames:

- injection to year-end 2001, using historical injection data;
- projected injection through year-end 2020 using maximum modeled injection rates; and
- a 10,000 year post-closure period.

A specific, conservative model strategy is developed for each model period (operational and post-operational). In order to allow for a *cumulative interval injection volume limitation* to replace the current well specific rate limitation, projected injection from year-end 2001 to year-end 2020 is modeled iteratively, successively using a maximum cumulative interval flow volume at each injection well location. Additionally, it is conservatively assumed that the specific well modeled in each model iteration injects at the maximum cumulative interval rate for the full projected time period from year-end 2001 through year-end 2020 (i.e., no shut-downs, etc.). These model runs are performed so that the plant will have the operational flexibility in the future to inject at rates higher than the currently approved maximum well limit of 350 gpm. The overly conservative assumption of modeling injection at the maximum sand cumulative injection rate at each well location results in a very conservative scenario for fluid movement and pressure buildup. Specific strategies employed are described below:

2.5.1 Model Strategy – Operational Pressure Model

For the Operational Pressure Model (*DuPont Multilayer Pressure Model*), in order to allow for a *cumulative interval injection volume limitation* as opposed to the current well specific rate limitation, projected injection from year-end 2001 to year-end 2020 is modeled iteratively, successively using a maximum cumulative interval flow volume at each injection well location. The injection interval sands are modeled as three distinct layer units:

1) Frio A/B/C Sand Injection Interval (former completion in both wells);

2) Frio E&F Sand Injection Interval (current completion – Plant Well 1 & 2); and

3) the Frio D Sand Injection Interval (modeled for protective purposes).

Conservatively assigned transmissibilities in the units are: 320,089 md-ft/cp in the Frio A/B/C Sand Injection Interval; 300,00 md-ft/cp in the Frio E&F Sand Injection Interval; and, 87,719 md-ft/cp in the Frio D Sand Injection Interval. Note that the overlying and underlying shale layers are modeled as being essentially impermeable (1×10^{-15} darcies) in order to prevent "bleed-off" of pressure from the modeled layer of interest. This is conservative as there will always be some pressure bleed-off through the overlying and underlying shale aquitard layers. The individual models are detailed below.

Frio A/B/C Sand Injection Interval

The Frio A/B/C Sand Injection Interval is conservatively modeled as a 150-foot layer with a permeability of 1,195 millidarcies and a viscosity of 0.56 centipoise (transmissibility = 320,089 md-ft/cp) in the *DuPont Multilayer Pressure Model*. Two cases are modeled for this sand:

1) Case 1 – Sealed Fault A Case; and

2) Case 2 – Open Fault Case.

To be conservative, in the prediction of pressure buildup with time, all of the historical flow down Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) is directly injected into the Frio A/B/C Sand in the model simulations (both Case 1 and Case 2 models). Future injection is assigned as shown in Table 2-17. The Case 1 model considers historical and future potential injection into Atofina's Plant Well 1 (WDW-122) and/or Plant Well 2 (WDW-230) [note that the wells are modeled as a single point source for computational ease], Cobra Operating's Texas Northern Railroad #6 saltwater disposal well, Equistar's Plant Well 1 (WDW-36), and Merisol's Plant Well 1 (WDW-147) and/or Plant Well 2 (WDW-319). Note that the Equistar Plant Well 1 (WDW-36) has not been used on a sustained basis since 1980 and would only be used in the unlikely event that both Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) were inoperative (the Equistar stream is currently injected into Lyondell's wells, see Section 1), therefore, including this well in the modeling is conservative.

The Case 1 model conservatively considers Fault A as a linear flow and pressure barrier of infinite extent, and models the Clinton Dome Boundary/Frio B Sand Pinchout as a curved no-flow barrier (see Section 2.4.13.2.1). Model input "image" injection wells are used in the Case

1 models to produce a boundary for Clinton Dome. The image wells are located and rate proportioned as determined following the "streamlines methodology" developed by Wattenbarger and Associates (see Appendix 2-6, Volume 3). The assumptions of the Streamline Model are the same as the DuPont Models. That is, the reservoir is infinite, isotropic, homogeneous, constant thickness, and two-dimensional. The Clinton Dome "image" injection wells are discussed in Section 2.4.17.2.1. Matthews, Brons, and Hazebroek (1954) used image well theory to develop drainage patterns for a number of difference drainage shapes. They used infinite numbers of image wells to calculate finite drainage areas. In applying their method to actual multi-well reservoirs, they showed that each well's drainage area is proportional to its flow rate, with no-flow boundaries being established between any two wells. For approximating no-flow boundaries in the DuPont model, a trial-and-error approach was taken to find the rates and locations of image wells that would approximate estimated actual boundaries. When the image well was correctly placed at the correct rate, none of the streamlines from the actual injection well would cross the desired no-flow boundary. Likewise, none of the streamlines from the image wells cross the no-flow boundary.

Case 2 considers Fault A to be horizontally transmissive (as well as all of the Renee-Lynchburg Field faults. This potentially brings all of the Houston Ship Channel Class I injection wells into pressure communication with the Frio A/B/C Sand Injection Interval. The Clinton Dome Boundary/Frio B Sand Pinchout is conservatively modeled as an implicit boundary of infinite extent. For computational ease, injection at the offset facilities with two wells (Atofina, GNI, Hampshire, Merisol, and Shell) is summed and is placed into the closest well to Lyondell.

Frio E&F Sand Injection Interval

The Frio E&F Sand is modeled as a 150-foot layer with a permeability of 1,200 millidarcies and a viscosity of 0.57 centipoise (transmissibility of 315,789 md-ft/cp) in the *DuPont Multilayer Pressure Model*. Two cases are modeled for this sand:

1) Case 1 – Sealed Fault A Case; and

2) Case 2 – Open Fault Case.

Future injection into the Frio E&F Sand Injection Interval is assigned as shown in Table 2-18.

Case 1 Sealed Fault Case

The Case 1 model considers historical and future potential injection into Atofina's Plant Well 1 (WDW-122) and/or Plant Well 2 (WDW-230) [note that the wells are modeled as a single point source for computational ease], and Merisol's Plant Well 1 (WDW-147) and/or Plant Well 2 (WDW-319). The Case 1 model also considers historical and future potential injection into Equistar's Plant Well 1 (WDW-36). This well has not been used on a sustained basis since 1980 and would only be used in the unlikely event that both Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) were inoperative (the Equistar stream is currently injected into Lyondell's wells, see Section 1). Therefore, allocating future injection in the Frio E&F Sand at both Lyondell and Equistar is overly conservative. The Case 1 model conservatively considers Fault A as a linear flow barrier of infinite extent and models the Clinton Dome Boundary as a curved no-flow barrier (see Section 2.4.13.2.1).

Model input "image" injection wells are used in the Case 1 models to produce a boundary for Clinton Dome. The image wells are located and rate proportioned as determined following the "streamlines methodology" developed by Wattenbarger and Associates (see Appendix 2-6, Volume 3). The assumptions of the Streamline Model are the same as the DuPont Models. That is, the reservoir is infinite, isotropic, homogeneous, constant thickness, and two-dimensional. The Clinton Dome "image" injection wells are discussed in Section 2.4.17.2.1. Matthews, Brons, and Hazebroek (1954) used image well theory to develop drainage patterns for a number of difference drainage shapes. They used infinite numbers of image wells to calculate finite drainage areas. In applying their method to actual multi-well reservoirs, they showed that each well's drainage area is proportional to its flow rate, with no-flow boundaries being established between any two wells. For approximating no-flow boundaries in the DuPont model, a trial-and-error approach was taken to find the rates and locations of image wells that would approximate estimated actual boundaries. When the image well was correctly placed at the correct rate, none of the streamlines from the actual injection well would cross the desired no-flow boundary. Likewise, none of the streamlines from the image wells cross the no-flow boundary.

Case 2 Open Fault Case

Case 2 considers Fault A to be horizontally transmissive (as well as all of the Renee-Lynchburg Field faults. This potentially brings all of the Houston Ship Channel Class I injection wells into pressure communication with the Frio E&F Sand Injection Interval. The Clinton Dome Boundary Pinchout is conservatively modeled as an implicit boundary of infinite extent. For computational ease, injection at the offset facilities with two wells (Atofina, GNI, Hampshire, Merisol, and Shell) is summed and is placed into the closest well to Lyondell.

Frio D Sand Injection Interval

The Frio D Sand is modeled as a 50-foot layer with a permeability of 1,000 millidarcies, and a viscosity of 0.57 centipoise (transmissibility = 87,719 md-ft/cp) in the *DuPont Multilayer Pressure Model.* Only a Case 1 model is run for the Frio D Sand. The line of sand absence, located southwest of the Channelview Plant, can be projected across the southwestern portion of the 2.5-mile radius Area of Review, which completely separates the modeled injection interval from the Houston Ship Channel injection facilities. Note that employing this methodology is conservative as it sets up a linear barrier of infinite extent and discounts the continuity of the Frio D Sand in several locations along the shale-out line. The line of sand absence is set to intersect the modeled Fault A linear barrier, thereby, resulting in two potential no flow barriers in the Case 1 models. For computational ease in the Case 1 modeling of the Frio D Sand Injection Interval, an angle of intersection of 120° is used for the two-modeled linear barriers. This results in two image well locations to properly image the Lyondell well field (360° divided by 120°). A schematic drawing of the Case 1 model boundaries in the Frio D Sand is shown in Figure2-19. Historical injection is assigned to the Frio D Sand based on the casing leak present in Plant Well 1 (WDW-148) during 1995 and 1996. All of the flow down Plant Well 1 (WDW-148) is directly injected into the Frio D Sand in the model simulation starting after the 1995 annual mechanical integrity test (no leak detected) to the time at which Plant Well 1 (WDW-148) was sidetracked in the autumn of 1996. Future injection is assigned as shown in Table 2-19.

2.5.2 Model Strategy – Operational Plume Model

For the Operational Plume Model (*DuPont Basic Plume Model*), in order to allow for a *cumulative interval injection volume limitation* as opposed to the current well specific rate limitation, projected injection from year-end 2001 to year-end 2020 is modeled iteratively, successively using a maximum cumulative annual interval flow volume at each injection well location for each injection interval sand. The sands are modeled as distinct layer units: Frio A/B/C Sand; Frio E&F Sand; and, the Frio D Sand. Note that the critical model parameters for the *DuPont Basic Plume Model* are injection volume, multiplying factor, sand thickness, and sand porosity. No other model inputs affect the generated results (i.e., varying permeability has no affect). For the historical and future time period in the Frio A/B/C Sand it is assumed that all of the flow went into the modeled thin 50-foot interval (i.e., interval is modeled with 100 percent of the historical volume into a single 50 foot layer). This is an overly conservative assumption since historical temperature logging and radioactive tracer surveys show that more than one of the sands has taken flow. The individual models are detailed below.

Frio A/B/C Sand Injection Interval

The Frio A/B/C Sand Injection Interval is conservatively modeled as a 50-foot layer with a porosity of 27 percent (ϕ-h = 13.5 pu-ft) in the *DuPont Basic Plume Model.* Two cases are modeled for this sand:

1) Case 1 – Sealed Fault A Case; and

2) Case 2 – Open Fault Case.

To be conservative in the depiction of plume geometry with time, all of the historic flow down Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) is directly injected into the Frio A/B/C Sand in the model simulations (both Case 1 and Case 2 models). Future injection is assigned as shown in Table 2-17.

Case 1 Sealed Fault A Case

The Case 1 model considers historical and future potential injection into Atofina's Plant Well 1 (WDW-122) and/or Plant Well 2 (WDW-230) [note that the wells are modeled as a single point source for computational ease], Cobra Operating's Texas Northern Railroad #6 well, Equistar's Plant Well 1 (WDW-36), and Merisol's Plant Well 1 (WDW-147) and/or Plant Well 2 (WDW-319). The Equistar's Plant Well 1 (WDW-36) has not been used on a sustained basis since 1980 and would only be used in the unlikely event that both Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) were inoperative (the Equistar stream is currently injected into Lyondell's wells, see Section 1), therefore, including this well in the modeling is conservative. The Case 1 model conservatively considers Fault A as a linear flow barrier of infinite extent and models the Clinton Dome Boundary/Frio B Sand Pinchout as a curved no-flow barrier (see Section 2.4.13.2.1).

Case 2 Open Fault Case

Case 2 considers Fault A to be horizontally transmissive (as well as all of the Renee-Lynchburg Field faults. This potentially brings all of the Houston Ship Channel Class I injection wells into communication with the Frio A/B/C Sand Injection Interval. The Clinton Dome Boundary/Frio B Sand Pinchout is conservatively modeled as an implicit boundary of infinite extent, as in the *DuPont Multilayer Pressure Model*. For computational ease, injection at the offset facilities with two wells (Atofina, GNI, Hampshire, Merisol, and Shell) is summed and is placed into the closest well to Lyondell.

Frio E&F Sand Injection Interval

The Frio E&F Sand is modeled as a 150-foot layer with a porosity of 27 percent (ϕ-h = 40.5 pu-ft) in the *DuPont Basic Plume Model*. Two cases are modeled for this sand:

1) Case 1 – Sealed Fault A Case; and

2) Case 2 – Open Fault Case.

To be conservative in the depiction of plume geometry with time, all of the historic flow down Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) is directly injected into the Frio E&F Sand in the model simulations (both Case 1 and Case 2 models). Future injection is assigned as shown in Table 2-18.

Case 1 Sealed Fault Case

The Case 1 model considers historical and future potential injection into Atofina's Plant Well 1 (WDW-122) and/or Plant Well 2 (WDW-230) [note that the wells are modeled as a single point source for computational ease], and Merisol's Plant Well 1 (WDW-147) and/or Plant Well 2 (WDW-319). The Case 1 model also considers historical and future potential injection into Equistar's Plant Well 1 (WDW-36). This well has not been used on a sustained basis since 1980 and would only be used in the unlikely event that both Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) were inoperative (the Equistar stream is currently injected into Lyondell's wells, see Section 1). Therefore, considering simultaneous future injection at both Lyondell and Equistar is conservative. The Case 1 model conservatively considers Fault A as a linear flow barrier of infinite extent and models the Clinton Dome Boundary as a curved no-flow barrier (see Section 2.4.13.2.1).

Case 2 Open Fault Case

Case 2 considers Fault A to be horizontally transmissive (as well as all of the Renee-Lynchburg

Field faults. This potentially brings all of the Houston Ship Channel Class I injection wells into communication with the Frio E&F Sand Injection Interval. The Clinton Dome Boundary Pinchout is conservatively modeled as an implicit boundary of infinite extent, as in the *DuPont Multilayer Pressure Model.* For computational ease, injection at the offset facilities with two wells (Atofina, GNI, Hampshire, Merisol, and Shell) is summed and is placed into the closest well to Lyondell.

Frio D Sand Injection Interval

The Frio D Sand is modeled as a 50-foot layer with a porosity of 27 percent (ϕ-h = 13.5 pu-ft) in the *DuPont Basic Plume Model.* Only a Case 1 model is run for the Frio D Sand. This line of sand absence can be projected across the southwestern portion of the 2.5-mile radius Area of Review, which completely separates the modeled injection interval from the Houston Ship Channel injection facilities. Note that employing this methodology is conservative as it sets up a linear barrier of infinite extent and discounts the continuity of the Frio D Sand in several locations along the shale-out line. The line of sand absence is set to intersect the modeled Fault A linear barrier, thereby, resulting in two potential no flow barriers in the Case 1 models. For computational ease in the Case 1 modeling of the Frio D Sand Injection Interval, an angle of intersection of 120^o is used for the two-modeled linear barriers. This results in two image well locations to properly image the Lyondell well field (360^o divided by 120^o). A schematic drawing of the Case 1 model boundaries in the Frio D Sand is shown in Figure 2-19. Historical injection is assigned to the Frio D Sand based on the casing leak present in Plant Well 1 (WDW-148) during 1995 and 1996. All of the flow down Plant Well 1 (WDW-148) is directly injected into the Frio D Sand in the model simulation starting after the 1995 annual mechanical integrity test (no leak) to the time at which Plant Well 1 (WDW-148) was sidetracked in autumn 1996. Future injection is assigned as shown in Table 2-19.

2.5.3 Model Strategy – Vertical Permeation Model

Vertical permeation is only calculated for the shale layer overlying the shallowest injection interval, the Frio D Sand Injection Interval. Since this is the shallowest requested interval, vertical permeation of injectate and formation fluid from the underlying Frio E&F Sand Injection Interval and/or the Frio A/B/C Sand Injection Interval would not extend vertically as far due to pressure bleed off into the Frio D Sand in the case of injection into the Frio E&F Sand Injection Interval and due to pressure bleed off into the Frio D Sand and Frio E&F Sand in the case of injection into the current completions (Frio E&F Sand Injection Interval). The *DuPont Vertical Permeation Model* is virtually identical to that employed for simulating pressure buildup in the Frio D Sand Injection Interval. The major difference between the two models is that in the *DuPont Vertical Permeation Model*, the shale overlying the Frio D Sand (Confining Shale Model Layer 13) is assigned a conservative upper bound permeability of 1.7 x 10^{-06} darcies, which allows for permeation of formation fluid and injectate into the shale. The employed permeability value exceeds local area whole core data by at least an order of magnitude and will result in an over estimate of vertical permeation of injectate and formation brine during the operational and post-operational period. Additionally, the model shale layer overlying the Frio D Sand (Confining Shale Model Layer 13) is conservatively assigned an upper-bound compressibility (α) value of 7.0 x 10^{-05} psi^{-1} (see Section 3.2.3, Appendix 2-3) for the upward permeation modeling case.

2.5.4 Model Strategy – 10,000 Year Vertical Model

Conservative concentration reduction factors are calculated for the constituents of interest by dividing the published health-based standard (or method detection limit) of the constituent by the maximum modeled concentration of the constituent. Use of maximum modeled waste stream concentrations ensures conservatism since actual average constituent concentrations are much lower. This, coupled with overly conservative effective constituent diffusivities results in clear overpredictions of the extent of long-term plume geometry. Additionally, potential waste transformation reactions are ignored, also resulting in conservatism.

2.5.5 Model Strategy – 10,000 Year Plume Model

Model strategy for the post-injection period or 10,000-year time frame is to model the endpoints of the requested three-month running average specific gravity range for each injection interval. Conceptual modeling demonstrates that effluent plumes will travel as an average, both during injection (due to mixing in the near-well area) and over the post-closure period (due to mixing of the drifting plume by dispersion), as shown in Fahy et al., 1992; Larkin et al., 1992; Larkin et al., 1993; Larkin et al., 1994 (see Appendix 2-6, Volume 5). Conceptual modeling of a three-month average was conducted under a joint effort by DuPont, the Texas Chemical Council, and EPA to investigate the effects of short-term effluent density (or specific gravity) variations on long term (10,000 year) plume movement. The studies were conducted to determine the viability of employing a range of three-month effluent density (or specific gravity) averages in lieu of the restrictive use of an instantaneous effluent limit. The Texas Chemical Council worked closely with EPA staff in preparing the required simulation runs for the modeling study, culminating in a report entitled *Modeling Effect of Input Parameter and Density Changes on Disposal Well Plumes* submitted to the EPA by the Texas Chemical Council. EPA concluded on July 19, 1995, (letter from Mr. Myron Knudson, Director Water Management Division to Mr. Mark Cheesman, UIC Subcommittee Chair - Texas Chemical Council) that modeling simulation runs successfully reinforced the results of previous studies, in summary that, a three-month weighted average effluent specific gravity is appropriate for facilities not injecting a significant amount of immiscible fluids. The Lyondell Chemical Company, Channelview Plant meets this criterion, since the effluent is mostly water containing only minor quantities of organics and dissolved salts.

Historic and projected injection (through the end of 2020) is determined for each injection interval based on the flow allocations used in the operational plume modeling. Total allocated volumes are determined from the *DuPont Basic Plume Model* using a Multiplying Factor of 1.0 (i.e., plug flow). Plume volume is then input as a "nominal plume radius" into the *DuPont 10,000-Year Waste Plume Model*. For purposes of the model simulation, all injection is ceased at the end of the year 2020 (including offsite injection). For the high specific gravity model simulations, nominal plume radii are calculated using thicknesses from the operational period modeling. For the low specific gravity model simulations, nominal plume radii are calculated using thicknesses representative of the Victor Blanco/Alco-Mag Field geographic areas located north-northwest of the facility.

Two different plume specific gravity cases are run for each injection interval sand. Long-term modeling uses a specific gravity range of 1.028 (lower end) to 1.100 (upper end). The specific gravity of the Frio formation fluid is 1.074 (see Section 2.4.9). In order to keep relationships between the various modeled fluids consistent and for ease of compliance verification, modeled input values are set in terms of specific gravity at ambient conditions. This approach is valid since the *DuPont 10,000 Year Waste Plume Model* is isothermal and model uses the difference in specific gravity (or density) to produce the driving force for buoyant plume movement, not the actual numerical values.

In each model case, it is assumed that total injection into the interval is of the same constant specific gravity (either the lower bound or upper bound three-month running specific gravity). This is very conservative, since the actual specific gravity of the waste stream is approximately 1.040 at 60 °F and has historically fallen well within the bounds of the requested range (see

Figures 2-9 and 2-10) on a daily basis. The specific gravity of the waste stream is expected to continue to fluctuate within historical limits in the future. Therefore, the average specific gravity of the plume at year-end 2020 will fall well within the range modeled, resulting in less long-term transport.

The High Specific Gravity Plume is heavier than the formation fluid and therefore will move down-dip or eastward due to buoyancy effects. In order to project the maximum amount of down-dip plume movement, the High Specific Gravity Plume case for each injection interval is run with a natural background groundwater velocity of 1.62 feet per year to the east. The natural background groundwater velocity is simulated in the model through the use of constant velocity input, which is maintained throughout the 200-year evaluation period. It can confidently be stated that at the Lyondell Chemical Company site, injected effluent plumes that are higher in specific gravity than the native formation brines present no environmental danger or risk to human health or the environment since they have no buoyant vertical driving force that would result in plume movement to shallower depths (i.e., they are confined between aquiclude layers). Due to density effects, modeling results have shown that high specific gravity effluent plumes, like those that may be injected at the Lyondell Chemical Company site, will in fact tend to "sink", moving deeper into the subsurface, thereby increasing the amount of vertical separation of the plume from the environment and underground sources of drinking water. The area immediately downdip of the site consists of uninterrupted homoclinal dipping strata. This area has been penetrated by multiple oil and gas test wells, which have found no hydrocarbons in the lower Frio section. It is unlikely that any additional testing that would find hydrocarbons in the lower Frio. Therefore, it is appropriate to evaluate the High Specific Gravity Plume over a shorter time span. A conservative time period of 200 years is chosen for the evaluation period. Formation pressures will have decayed and no Cone of Influence capable or driving effluent out of the injection interval is present well within this 200-year time period. Therefore, after 200 years, there will be no driving force to move the High Specific Gravity Plume to shallower intervals.

The Low Specific Gravity Plume is lighter than the formation fluid and will move up-dip (north-northwest) from the plant due to buoyancy effects. In order to maximize the amount of horizontal movement in the 10,000-year time frame, no background groundwater velocity is used for the low specific gravity model cases. The only driving force for plume movement is buoyancy due to the density contrast between the waste and formation fluid.

2.5.5.1 Model Strategy – 10,000 Year Plume Model Computation Grid Area

The computational region of the DuPont 10,000 Year Waste Plume Model is defined by the YINF and XNINF parameters contained in the model input .job files and the number and size of the model grid blocks (NX and NY in the .prm file). The model uses a moving coordinate system with time that is designed to keep the waste plume within the computational area. Lyondell has included an example of the DuPont 10,000 Year waste Plume Model Grid computational region for the Frio A/B/C Sand Injection Interval Low Specific Gravity Plume in Appendix 2-6. The example shows that the plume is maintained within the computational area and away from the model edges.

2.6 Model Calibration with Historical Data

Model calibration involves generating the model-predicted flowing and shut-in pressure response and comparing it to the observed, historical, flowing, and shut-in static well pressures. The purpose of model calibration is to confirm that the reservoir boundary and geologic parameters used in the model produce a conservative estimate of the injection pressure response with time (and injected volume).

2.6.1 Model Calibrations with Formation Pressure – Frio A/B/C Sand Injection Interval

Formation flowing bottomhole pressure predictions from the *DuPont Multilayer Pressure Model* (modeled at a reference depth of 6,884 feet for the Frio A/B/C Sand Injection Interval) are compared to measured formation flowing pressures (corrected for well skin effects) to ensure that the model using a transmissibility of 320,089 md-ft/cp is conservative. Two model comparison cases are made using the *DuPont Multilayer Pressure Model*:

a) Case 1 – Sealed Fault A Case; and

b) Case 2 – Open Fault Case, using historical data from each injection well.

Average injection rates are used in each month, except during months when an injection/falloff test or an interference test was run. During these months, injection is set to equal the stabilized test injection rate (see Appendix 2-7, Volumes 13 through 15). Measured formation flowing pressures are established by analyzing injectivity/falloff test data and extrapolating bottomhole flowing pressures from gauge depth to model formation depths (sand top depths). Injection is set to "0" during the months that a static bottomhole pressure was taken in a well.

2.6.1.1 Input Parameters

The process of model calibration is interactive because geologic and reservoir inputs can be adjusted, within a range of possible values, until a conservative estimate of the predicted flowing and shut-in pressure history is achieved. The fundamental reservoir parameters that can be varied in the calibration process for the *DuPont Multilayer Pressure Model* are transmissibility

(kh/μ), storativity ($\phi c_t h$), and the position and distance to the modeled flow barriers in the reservoir.

An initial estimate of model parameters comes from empirical site-specific data such as static bottomhole pressure tests, injection/falloff tests, core data, geophysical well logs, etc. Additional data are available from literature sources and the geologic analysis of the area surrounding the Channelview Plant. Final model input parameters, after the calibration process, yield a model-predicted flowing and shut-in pressure that are greater than the measured historical flowing and shut-in pressures. Model parameters for the sand layers that were not directly calibrated by shut-in pressure matching (Frio E&F Sand Injection Interval and the Frio D Injection Interval) are inferred from the calibrated Frio A/B/C Sand Injection Interval.

Static and flowing pressures measured in Lyondell's Plant Well 1 (WDW-148 and Plant Well 2 (WDW-162) during injection/falloff and shut-in tests through March 2002, are used in the calibration of the Frio A/B/C Sand Injection Interval. Flowing bottomhole pressures have been corrected for skin effects using the derived transmissibility, test rate, and skin at the time of the injection/falloff test. Both flowing and shut-in pressures have been adjusted to a common datum of 6,884 feet (reference depth at the top of the sand) using the wellbore gradient taken at the time of the survey.

Average monthly volumes, converted to an average volumetric rate in gallons per minute, are used in the model calibration runs (see Appendix 2-6). The DuPont Deepwell Models use standardized time increments for the models. The standard month is 30.4375 days, which is used for the calibration model runs. The conversion is:

Gallons / minute = Reported Volume (gals/month) / [(365.25 days/year) x (1 year / 12 month) x (1440 minute/day)]

For the flowing calibrations in each injection interval, the injection rate at the time of the test is used in the model for that month. In addition, a rate of zero is used for the entire month for the shut-in calibrations.

The shut-in calibrations are very conservative because the 730-hour model shut-in over predicts the historic falloff test shut-in pressures in all cases. The model would over predict the well shut-in pressures by a greater amount if the observed shut-in pressures were corrected to the same duration as the model. The observed falloff tests are typically less than 24 hours, yielding a higher "static" pressure than would be observed if the well were to remain shut-in for 730 hours during the falloff test.

Two model cases are considered in this 2000 HWDIR Exemption Petition Reissuance for each injection interval. A summary of each modeling scenario is present below:

Case 1 - accounts for the no-flow boundary imposed by the Clinton Dome/Frio B Sand Pinchout west of the Channelview Plant and the potential no-flow boundary possibly imposed by the Renee-Lynchburg Faults, located to the south and southeast, near the 2.5-mile radius Area of Review boundary. In Case 1, image injector wells are used to create the modeled no-flow boundary for Clinton Dome/Frio B Sand Pinchout, as described by the geologic model using the theory of streamlines, and a model implicit linear no-flow boundary (identified as two points on the projected trend line of Fault A) is used for the Renee-Lynchburg Field faults.

Case 2 - accounts for the no-flow boundary imposed by the Clinton Dome/Frio B Sand Pinchout as a model implicit linear no-flow boundary (identified as two points on the projected trend line. Case 2 assumes that the Renee-Lynchburg Field faults southeast of the Channelview Plant are transmissive, allowing pressure communication with the Houston Ship Channel Class I injection wells. Since the Renee-Lynchburg faults are assumed to be transmissive in Case 2, the entire injection history, from 1957 through March 2002, for wells at the nearby facilities with actual or potential injection into each of the injection intervals is included in the model. For these wells, all injection is assumed to flow into the Frio A/B/C Sand Injection Interval.

A model run "JOB" file is used as the input deck to the *DuPont Multilayer Pressure Model* and contains a complete listing of the rate history and layer properties used in the final model calibration run for each case. A detailed discussion of the model calibration process and results are described in the following subsections.

2.6.1.2 Calibration Results, Case 1 – Sealed Fault A Model Case

Case 1 – Sealed Fault Case calibration models were prepared for the Frio A/B/C Sand Injection Interval using a transmissivity of 320,089 md-ft/cp. A separate model was prepared for the flowing model calibration (uses injection/falloff test injection rates during the testing "month") for each well and for the shut-in static well calibration (uses zero injection during the testing "month"). Model cases for each well are identified below, copies of the model input and output files are contained in Appendix 2-7.

Frio A/B/C Sand Injection Interval – Well 1 (WDW-148)	**Model Job File Name**
Flowing Pressure Calibration	abccal_flta_bshale_w1.job
Shut-in Pressure Calibration	abccal_flta_bshale_w1si.job
Frio A/B/C Sand Injection Interval – Well 2 (WDW-162)	**Model Job File Name**
Flowing Pressure Calibration	abccal_flta_bshale_w2.job
Shut-in Pressure Calibration	abccal_flta_bshale_w2si.job

From 1999 through 2002, Lyondell ran an interference test at the end of the standard injection/falloff test in Plant Well 1 (WDW-148). For the interference testing, the injection rate in Plant Well 2 (WDW-162) is increased to a steady high rate, and the interference pressure is observed in Plant Well 1 (WDW-148). A model case for the interference testing is also run in the calibration and is identified below, copies of the model input and output files are contained in Appendix 2-7.

Frio A/B/C Sand Injection Interval – Well 1 (WDW-148)	**Model Job File Name**
Flowing Pressure Calibration – Interference Testing	abccal_flta_bshale_w1intr.job

<u>Frio A/B/C Sand Injection Interval</u>

Figure 2-20 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 1 using a transmissivity of 320,089 md-ft/cp, with the calculated, skin and depth adjusted, flowing bottomhole injection pressures taken in Lyondell's Plant Well 1 (WDW-148) over the time period between 1991 and 1996, prior to sidetracking. The solid line in Figure 2-20, which conservatively overmatches all of the data points from 1991 to 1996, is the Case 1 – Sealed Fault Case model response (transmissivity of 320,089 md-ft/cp), and the red-square points on the graph are the calculated flowing bottomhole injection pressures in the well, corrected to the reference depth. Figure 2-21 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 1 with the calculated, skin and depth adjusted, flowing bottomhole injection pressures taken in Lyondell's Plant Well 1 (WDW-148) over the time period between 1997 and 2002, following sidetracking of the well. The solid line in Figure 2-21, which conservatively overmatches all of the data points from 1997 to 2002, is the Case 1 – Sealed Fault Case model response, and the red-square points on the graph are the adjusted, measured, flowing bottomhole injection pressures. Figure 2-22 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 1 with the measured depth adjusted, flowing bottomhole interference injection pressures taken in the observation well (Lyondell's Plant Well 1 (WDW-148)) over the time period between 1999 and 2002. The solid line in Figure 2-22, which conservatively overmatches all of the data points from 1999 to 2002, is the Case 1 – Sealed Fault Case model response, and the red-diamond points on the graph are the adjusted, measured, flowing bottomhole interference injection pressures from Plant Well 2 (WDW-162). Figure 2-23 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 1 with the calculated, skin and depth adjusted, flowing bottomhole injection pressures taken in Lyondell's Plant Well 2 (WDW-162) over the time period between 1990 and 1999. The solid line in Figure 2-23, which conservatively overmatches all of the data points from 1990 to 1999, is the Case 1 – Sealed Fault Case model response, is the Case 1 model response, and the red-square points on the graph are the adjusted, measured, flowing bottomhole injection pressures. Table 2-20 presents a numerical comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 1 - Sealed Fault A Case with the calculated, skin and depth adjusted, flowing bottomhole injection pressures taken in Lyondell's Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). The tabulation shows that the model predicted flowing bottomhole pressures over predict the measured responses, by a significant margin.

Figure 2-24 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response at a transmissivity of 320,089 md-ft/cp for Case 1 with the measured, depth adjusted, shut-in static well pressures taken in Lyondell's Plant Well 1 (WDW-148) over the time period from 1982 through 1996. The solid line in Figure 2-24 is the Case 1 shut-in model response, and the blue circular points on the graph are the depth adjusted, measured, shut-in pressures recorded at the end of an injection/falloff test period or on static shut-in of the well (pre-1990). The model over predicts all of the measured responses since surface read-out gauges run on wireline have been used starting in 1990. Note that when the shut-in calibration job is run for Well No. 1 (abccal_flta_bshale_w1si.job) the figure includes the month-end pressures for only the months that the injection rate is "zero" (i.e. no injection). Therefore, the solid red line in Figure 2-24 shows the month-end pressures for each month that the modeled well number 4 (original Plant Well 1 completion – L1) has a "zero" injection rate. This includes months that the well was shut-in during normal plant operations and the months that a static pressure was taken in the well (rate set to 0 gpm in the model). However, this also includes all the months before the well was placed into active injection (prior to July 1978) and all the months following the sidetrack of the well (October 1996).

Figure 2-25 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response at a transmissibility of 320,089 md-ft/cp for Case 1 with the measured, depth adjusted, shut-in static well pressures taken in Lyondell's Plant Well 1 (WDW-148) over the time period from 1997 through 2002, following sidetracking of the well. The solid line in Figure 2-25 is the Case 1 shut-in model response, and the blue circular points on the graph are the depth adjusted, measured, shut-in pressures recorded at the end of an injection/falloff test period. The model over predicts all of the measured responses since 1997 at the sidetrack well location. Note that when the shut-in calibration job is run for Well No. 1 (abccal_flta_bshale_w1si.job) the figure includes the month-end pressures for only the months that the injection rate is "zero" (i.e. no injection) in the sidetrack well. Therefore, the solid red line in Figure 2-25 shows the month-end pressures for each month that the modeled well number 5 (sidetrack Plant Well 1 completion – L1A) has a "zero" injection rate. This includes months that the well was shut-in during normal plant operations and the months that a static pressure was taken in the well (rate set to 0 gpm in the model). However, this also includes all the months before the well was sidetracked and placed into active service in October 1996.

Figure 2-26 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response at a transmissibility of 320,089 md-ft/cp for Case 1 with the measured, depth adjusted, shut-in static well pressures taken in Lyondell's Plant Well 2 (WDW-162) over the time period from 1979 through 1999. The solid line in Figure 2-26 is the Case 1 shut-in model response, and the blue circular points on the graph are the depth adjusted, measured, shut-in pressures recorded at the end of an injection/falloff test period or on static shut-in of the well (pre-1990). The model over predicts all of the measured responses since 1986, with the only exception being in July 1993, which appears to be anomalously high (and is 36 psi higher than the corresponding pressure recorded in Plant Well 1 (WDW-148) at the same time). Table 2-20 presents a numerical comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 1 with the measured, depth adjusted, shut-in pressures taken in Lyondell's Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). Note that when the shut-in calibration job is run for Well No. 2 (abccal_flta_ bshale_w2si.job) the output injection well pressure graph includes the month-end pressures for only the specific months that the injection rate is "zero" (i.e. no injection into Plant Well 2). Therefore, the solid red line in Figure 2-26 shows the month-end pressures for each month that the modeled well number 6 (Plant Well 2 completion – L2) has a "zero" injection rate. This includes months that the well was shut-in during normal plant operations and the months that a static pressure was taken in the well (rate set to 0 gpm in the model). However, this also includes all the months before the well was placed into active injection, prior to January 1980. For the time period from start-up of Plant Well 2 (January 1980) to the end of the model run, a pressure is only shown for the months with no actual injection or where the injection was set to 0 gpm in the model due to a static pressure being taken during that month. During the 22 years of modeled service for Plant Well 2, there are only 24 months of no injection; therefore, only these 24 month-end pressures for this time period are depicted on the solid line in Figure 2-26. The modeled flowing pressures during active injection months are not shown on the graph during this time period.

2.6.1.3 Calibration Results, Case 2 – Open Fault Model Case

Case 2 – Open Fault Case calibration models were prepared for the Frio A/B/C Sand Injection Interval. A separate model was prepared for the flowing model calibration (uses injection/falloff test injection rates during the testing "month") for each well and for the shut-in static well calibration (uses zero injection during the testing "month"). Model cases for each well are identified below, copies of the model input and output files are contained in Appendix 2-7.

Frio A/B/C Sand Injection Interval – Well 1 (WDW-148)	**Model Job File Name**
Flowing Pressure Calibration	abccal_open_bshale_w1.job
Shut-in Pressure Calibration	abccal_open_bshale_w1si.job
Frio A/B/C Sand Injection Interval – Well 2 (WDW-162)	**Model Job File Name**
Flowing Pressure Calibration	abccal_open_bshale_w2.job
Shut-in Pressure Calibration	abccal_open_bshale_w2si.job

From 1999 through 2002, Lyondell had run an interference test at the end of the standard injection/falloff test in Plant Well 1 (WDW-148). For the interference testing, the injection rate in Plant Well 2 (WDW-162) is increased to a steady high rate, and the interference pressure is observed in Plant Well 1 (WDW-148). A model case for the interference testing is also run in the calibration and is identified below, copies of the model input and output files are contained in Appendix 2-7.

Frio A/B/C Sand Injection Interval – Well 1 (WDW-148)	**Model Job File Name**
Flowing Pressure Calibration – Interference Testing	abccal_open_bshale_w1intr.job

Frio A/B/C Sand Injection Interval

Figure 2-27 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response at a transmissibility of 320,089 md-ft/cp for Case 2 with the calculated, skin and depth adjusted, flowing bottomhole injection pressures taken in Lyondell's Plant Well 1 (WDW-148) over the time period between 1991 and 1996, prior to sidetracking. The solid line in Figure 2-27, which conservatively overmatches all of the data points from 1990 to 1996, is the Case 2 – Open Fault Case model response, and the red-square points on the graph are the adjusted, measured, flowing bottomhole injection pressures in the well.

Figure 2-28 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 2 with the calculated, skin and depth adjusted, flowing bottomhole injection pressures taken in Lyondell's Plant Well 1 (WDW-148) over the time period between 1997 and 2002, following sidetracking. The solid line in Figure 2-28, which conservatively overmatches all of the data points from 1997 to 2002, is the Case 2 – Open Fault Case model response, and the red-square points on the graph are the adjusted, measured, flowing bottomhole injection pressures.

Figure 2-29 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 2 with the measured depth adjusted, flowing bottomhole interference injection pressures taken in the observation well (Lyondell's Plant Well 1 (WDW-148)) over the time period between 1999 and 2002. The solid line in Figure 2-29, which conservatively overmatches all of the data points from 1999 to 2002, is the Case 2 – Open Fault Case model response, and the red-diamond points on the graph are the adjusted, measured, flowing bottomhole interference injection pressures from Plant Well 2 (WDW-162).

Figure 2-30 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response using a transmissivity of 320,089 md-ft/cp for Case 2 with the calculated, skin and depth adjusted, flowing bottomhole injection pressures taken in Lyondell's Plant Well 2 (WDW-162) over the time period between 1990 and 1999. The solid line in Figure 2-30, which conservatively overmatches all of the data points from 1990 to 1999, is the Case 2 – Open Fault Case model response, and the red-square points on the graph are the adjusted, measured, flowing bottomhole injection pressures. Table 2-21 presents a numerical comparison of the *DuPont*

Multilayer Pressure Model pressure response for Case 2 with the calculated, skin and depth adjusted, flowing bottomhole injection pressures taken in Lyondell's Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). The tabulation shows that the model predicted flowing bottomhole pressures over predict the measured responses, by a significant margin.

Figure 2-31 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response using a transmissivity of 320,089 md-ft/cp for Case 2 with the measured, depth adjusted, shut-in static well pressures taken in Lyondell's Plant Well 1 (WDW-148) over the time period from 1982 through 1996. The solid line in Figure 2-31 is the Case 2 shut-in model response, and the blue circular points on the graph are the depth adjusted, measured, shut-in pressures recorded at the end of an injection/falloff test period or on static shut-in of the well (pre-1990). The model over predicts all of the measured responses since surface read-out gauges were used in 1990. Note that when the shut-in calibration job is run for Well No. 1 (abccal_open_bshale_w1si.job) the figure includes the month-end pressures for only the months that the injection rate is "zero" (i.e. no injection). Therefore, the solid red line in Figure 2-31 shows the month-end pressures for each month that the modeled well number 4 (original Plant Well 1 completion – L1) has a "zero" injection rate. This includes months that the well was shut-in during normal plant operations and the months that a static pressure was taken in the well (rate set to 0 gpm in the model). However, this also includes all the months before the well was placed into active injection (prior to July 1978) and all the months following the sidetrack of the well (October 1996).

Figure 2-32 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 2 with the measured, depth adjusted, shut-in static well pressures taken in Lyondell's Plant Well 1 (WDW-148) over the time period from 1997 through 2002, following sidetracking of the well. The solid line in Figure 2-32 is the Case 2 shut-in model response, and the blue circular points on the graph are the depth adjusted, measured, shut-in pressures recorded at the end of an injection/falloff test period. The model over predicts all of the measured responses since 1997 at the sidetrack well location. Note that when the shut-in calibration job is run for Well No. 1 (abccal_open_bshale_w1si.job) the figure includes the month-end pressures for only the months that the injection rate is "zero" (i.e. no injection) in the sidetrack well. Therefore, the solid red line in Figure 2-32 shows the month-end pressures for each month that the modeled well number 5 (sidetrack Plant Well 1 completion – L1A) has a "zero" injection rate. This includes months that the well was shut-in during normal plant operations and the months that a static pressure was taken in the well (rate set to 0 gpm in the model). However, this also includes all the months before the well was sidetracked and placed into active service in October 1996.

Figure 2-33 shows a comparison of the *DuPont Multilayer Pressure Model* pressure response using a transmissibility of 320,089 md-ft/cp for Case 2 with the measured, depth adjusted, shut-in static well pressures taken in Lyondell's Plant Well 2 (WDW-162) over the time period from 1979 through 1999. The solid line in Figure 2-33 is the Case 2 shut-in model response, and the blue circular points on the graph are the depth adjusted, measured, shut-in pressures recorded at the end of an injection/falloff test period or on static shut-in of the well (pre-1990). The model over predicts all of the measured responses since 1986, with the only exception being in July 1993, which appears to be anomalously high (and is 36 psi higher than the corresponding static pressure recorded in Plant Well 1 at the same time). Table 2-21 presents a numerical comparison of the *DuPont Multilayer Pressure Model* pressure response for Case 2 with the measured, depth adjusted, shut-in pressures taken in Lyondell's Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). Note that when the shut-in calibration job is run for Well No. 2 (abccal_open_ bshale_w2si.job) the output injection well pressure graph includes the month-end pressures for only the specific months that the injection rate is "zero" (i.e. no injection into Plant Well 2). Therefore, the solid red line in Figure 2-33 shows the month-end pressures for each month that the modeled well number 6 (Plant Well 2 completion – L2) has a "zero" injection rate. This includes months that the well was shut-in during normal plant operations and the months that a static pressure was taken in the well (rate set to 0 gpm in the model). However, this also includes all the months before the well was placed into active injection, prior to January 1980. For the time period from start-up of Plant Well 2 (January 1980) to the end of the model run, a pressure is only shown for the months with no actual injection or where the injection was set to 0 gpm in the model due to a static pressure being taken during that month. During the 22 years of modeled service for Plant Well 2, there are only 24 months of no injection; therefore, only these 24 month-end pressures for this time period are depicted on the solid line in Figure 2-33. The modeled flowing pressures during active injection months are not shown on the graph during this time period.

2.6.2 Model Calibration – Frio E&F Sand Injection Interval

Model transmissibility in the Frio E&F Sand is set to a value of 315,789 md-ft/cp. This is conservative in comparison to the initial injection/falloff test conducted in the recompleted Plant Well 2 (WDW-162) in April 3003. Analysis of that test (see Appendix 2-6) showed a transmissibility of 569,038.2 md-ft/cp for the Frio E&F Sand at Lyondell. The assigned model transmissibility value in the Frio E&F Sand of 315,789 md-ft/cp is also conservative in comparison to the historic injection/falloff test conducted in Merisol's Plant Well 1 (WDW-147) as shown in Table 2-5.

2.7 Model Results

After performing a final review of the model input values and results of the model calibration, final iterative runs of the *DuPont Basic Plume, DuPont Multilayer Pressure, DuPont Multilayer Vertical Permeation, DuPont Molecular Diffusion,* and *DuPont 10,000 Year Waste Plume Models* were made. These model simulation runs considered projected injection into each well location from year-end 2001 through year-end 2020 at the maximum cumulative injection rate for each injection interval. The models results are used to show the conservative extent of waste movement, formation pressure distribution within a 2.5-mile radius Area of Review, extent of vertical waste permeation, and long-term transport under the revised conditions in this requested reissuance.

2.7.1 Current and Near Future Waste Distribution

The horizontal and vertical distributions of injected waste at year-end 2001 (historical period) and through the end of the year 2020 are presented. These results are obtained from the *DuPont Basic Plume* and *DuPont Multilayer Vertical Permeation Models* under the revised conditions requested in this reissuance request.

2.7.1.1 Horizontal Extent

Modeled plume extent in each injection interval is generated by the *DuPont Basic Plume Model*, which performs a single layer volumetric calculation. The initial model run for each of the injection intervals (and each model case) is a conservative prediction of the volumetric, or nominal, plume at year-end 2020. The nominal plume considers purely plug flow (i.e., no dispersion). Each of the plume models were then run a second time, incorporating the conservative Multiplying Factor of 3.8 to show the outermost perimeter of the operational plumes in the three injection intervals. Model results are discussed below.

2.7.1.1.1 Case 1 – Sealed Fault A Case Plume Models

The *DuPont Basic Plume Model* calculates the time-dependent lateral movement of waste emanating from the well(s) at an injection site. The model performs a single layer volumetric calculation using the porosity-thickness and the injection volumes. The nominal plume calculation considers purely plug flow (i.e., no dispersion). The nominal plume model includes the effects of multiple well interactions and a separate calculation is made for each injection interval into which waste is injected, has been injected, or is proposed to be injected.

Nominal plume model cases for the Case 1 – Sealed fault A Case models are contained in Appendix 2-10, Volume 17, and are identified below:

<u>Plume Model Runs – Well 1 (WDW-148)</u>		Appendix 2-10, Volume 17
Frio A/B/C Sand – Case 1	abcsand_clint_nominal_w1.job	
Frio E&F Sand – Case 1	efsand_clint_nominal_w1.job	
Frio D Sand – Case 1	dsand_clint_nominal_w1.job	
<u>Plume Model Runs – Well 2 (WDW-162)</u>		Appendix 2-10, Volume 17
Frio A/B/C Sand – Case 1	abcsand_clint_nominal_w2.job	
Frio E&F Sand – Case 1	efsand_clint_nominal_w2.job	
Frio D Sand – Case 1	dsand_clint_nominal_w2.job	

Nominal plumes for the Sealed Fault A Case models at year-end 2020 are presented in Figures 2-34 to 2-39. The figures show the plume extent with maximum injection iteratively placed into Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) for each of the three injection intervals. Additionally, a nominal plume sensitivity case for the Frio A/B/C Sand was also run using an effective interval of 30 feet for use in the Low Specific Gravity Plume Modeling. The nominal plume for this case is presented in Figure 2-40. Nominal plume diameters (along the longest axis) are presented in Table 2-22)

All model input volumes are then functioned by the Multiplying Factor of 3.8 (essentially a 3.8 fold multiplier) to produce the "disperse" operational plume. For the Frio A/B/C Injection Interval, all historical injection and future injection at the maximum injection rate of 700 gpm is considered. To be conservative in the depiction of plume geometry with time, all of the historic flow down Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) is also directly injected into the Frio E&F Sand in the model simulations, this conservatively accounts for the potential "leak" from the Frio A/B/C Sand Injection Interval into the overlying Frio E&F Sand Injection Interval that is observed on historic temperature logs. Future injection into the Frio E&F Sand Injection Interval is at the maximum rate of 700 gpm from year-end 2001 through year-end 2020. Historical injection is assigned to the Frio D Sand based on the casing leak present in Plant Well 1 (WDW-148) during 1995 and 1996. All of the flow down Plant Well 1 (WDW-148) is directly injected into the Frio D Sand in the model simulation starting after the 1995 annual mechanical integrity test (no leak) to the time at which Plant Well 1 (WDW-148) was sidetracked in autumn 1996. Future injection into the Frio D Sand Injection Interval is at the maximum rate of 425 gpm from year-end 2001 through year-end 2020.

The modeled plume extents for the three injection intervals are shown for year-end 2001 (maximum historical plume), and year-end 2020 (maximum operational plume) for each injection well. The plume plots are shown graphically in Figures 2-41 to 2-55). Note that both a detailed plume plot and a "large-scale" plume plot are shown at year-end 2020. The large-scale plot for each model case shows all of the plumes generated by the model, while the more detailed plots key into the 2.5-mile radius Area of Review.

Plume model cases for the Case 1 – Sealed Fault A Case models are contained in Appendix 2-10, Volume 17, and are identified below:

<u>Plume Model Runs – Well 1 (WDW-148)</u>		Appendix 2-10, Volume 17
Frio A/B/C Sand – Case 1	asand_clint_plume_w1.job	
Frio E&F Sand – Case 1	efsand_clint_plume_w1.job	
Frio D Sand – Case 1	dsand_clint_plume_w1.job	
<u>Plume Model Runs – Well 2 (WDW-162)</u>		Appendix 2-10, Volume 17
Frio A/B/C Sand – Case 1	asand_clint_plume_w2.job	
Frio E&F Sand – Case 1	efsand_clint_plume_w2.job	
Frio D Sand – Case 1	dsand_clint_plume_w2.job	

Operational plume diameters (measured along the longest axis) are presented in Table 2-23. Note that a portion of the conservatively modeled Frio A/B/C Sand Injection Interval extends slightly beyond the 2.5-mile radius Area of Review boundary, and potentially intersects additional artificial penetrations. These wells in the "extended operational plume" are considered in Section 3.0 – Area of Review.

2.7.1.1.2 Case 2 – Open Fault Case Plume Models

The Case 2 models assume that the Renee-Lynchburg cross-cutting faults are not barriers to pressure and/or fluid flow. This model case considers the potential effects of the Houston Ship Channel area injection wells on the Lyondell Chemical Company Channelview Plant wells. The nominal plume model includes the effects of multiple well interactions and a separate calculation is made for each injection interval into which waste, has been injected, is injected, or is proposed to be injected.

Nominal plume model cases for the Case 2 – Open Fault Case Models are contained in Appendix 2-10, Volume 17, and are identified below:

<u>Plume Model Runs – Well 1 (WDW-148)</u>		Appendix 2-10, Volume 17
Frio A/B/C Sand – Case 2	asand_open_nominal_w1.job	
Frio E&F Sand – Case 2	efsand_open_nominal_w1.job	
<u>Plume Model Runs – Well 2 (WDW-162)</u>		Appendix 2-10, Volume 17
Frio A/B/C Sand – Case 2	asand_open_nominal_w2.job	
Frio E&F Sand – Case 2	efsand_open_nominal_w2.job	

Nominal plumes for the Open Fault Case models at year-end 2020 are presented in Figures 2-56 to 2-59. The figures show the plume extent with maximum injection iteratively placed into Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) for the Frio A/B/C Sand Injection Interval and the Frio E&F Sand Injection Interval. Note that nominal plume cases were not run for the Frio D Sand Injection Interval, extension of the potential line of sand pinch-out shows that the sand is separated from the Houston Ship Channel Area injection well facilities. Nominal plume diameters (along the longest axis) are presented in Table 2-22 for the Case 2 – Open Fault Case Models.

All model input volumes are then functioned by the Multiplying Factor of 3.8 (essentially a 3.8 fold multiplier) to produce the "disperse" operational plume. For the Frio A/B/C Injection Interval, all historical injection and future injection at the maximum injection rate of 700 gpm is considered. To be conservative in the depiction of plume geometry with time, all of the historic flow down Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) is also directly injected into the Frio E&F Sand in the model simulations, this conservatively accounts for the potential "leak" from the Frio A/B/C Sand Injection Interval into the overlying Frio E&F Sand Injection Interval. Future injection into the Frio E&F Sand Injection Interval is at the maximum rate of 700 gpm from year-end 2001 through year-end 2020. Note that plume cases were not run for the Frio D Sand Injection Interval, extension of the potential line of sand pinch-out shows that the sand is separated from the Houston Ship Channel Area injection well facilities..

The modeled plume extents for the three injection intervals are shown for year-end 2001 (maximum historical plume), and year-end 2020 (maximum operational plume) for each injection well. The plume plots are shown graphically in Figures 2-60 to 2-69). Note that both a detailed plume plot and a "large-scale" plume plot are shown at year-end 2020. The large-scale plot for each model case shows all of the plumes generated by the model, while the more detailed plots key into the 2.5-mile radius Area of Review.

Plume model cases are contained in Appendix 2-10, Volume 17, and are identified below:

Plume Model Runs – Well 1 (WDW-148)		Appendix 2-10, Volume 17
Frio A/B/C Sand – Case 2	asand_open_plume_w1.job	
Frio E&F Sand – Case 2	efsand_open_plume_w1.job	
Plume Model Runs – Well 2 (WDW-162)		Appendix 2-10, Volume 17
Frio A/B/C Sand – Case 2	asand_open_plume_w2.job	
Frio E&F Sand – Case 2	efsand_open_plume_w2.job	

Operational plume diameters (measured along the longest axis) are presented in Table 2-23. Note that a portion of the conservatively modeled Frio A/B/C Sand Injection Interval extends slightly beyond the 2.5-mile radius Area of Review boundary, and potentially intersects additional artificial penetrations. These wells in the "extended operational plume" are considered in Section 3.0 – Area of Review.

2.7.1.2 Vertical Extent

The extent of vertical movement at the end of 2020 is based on the output of the *DuPont Multilayer Vertical Permeation Model* (.UPP file). The results of the model depict movement of formation water and injected waste into, but not through, aquicludes adjacent to the injection reservoir.

In the aquiclude layer overlying the Frio D Sand, the maximum upward permeation will not exceed 14 feet at the projected maximum injection rate of 425 gpm into Plant Well 1 (WDW-148) or Plant Well 2 (WDW-162) (Figure 2-70). A summary at the maximum injection rate of the upward permeation results in the aquiclude layer (Shale Layer 13) directly above the Frio D Sand injection layer is shown in Appendix 2-9, Volume 17, and is identified below:

Vertical Permeation Model Run	Dsand_flta_permeation_w1.job	Appendix 2-9, Volume 17

Figure 2-70 shows a graph of the vertical permeation with time into the Frio Containment Shale Layer (Model Layer 13).

2.7.1.3 Pressure Distribution within the Area of Review

Whenever waste is injected into a subsurface geologic formation, the pressure within the reservoir increases. This pressure increase is highest at the wells and decreases with lateral distance. The *DuPont Multilayer Pressure Model* is used to determine the pressure distribution within the injection interval and at the point of injection. The model is an extension of an earlier treatment presented by Miller et al. (1986) that is based on the Theis equation (Theis, 1935). Note that in the modeling, pressure communication cannot occur by permeation through aquicludes, which are sent to be impermeable.

Since the model calibration shows that the historic models conservatively over estimate the measured shut-in static pressures and flowing bottomhole injection pressures (corrected for well skin effects), the projected maximum buildup pressures will also be conservative and will be gross over estimates for future injection interval pressures.

Maximum pressure buildup model runs have been made for both the Case 1 – Sealed Fault A Case and the Case 2 – Open Fault Case for the Frio A/B/C Sand Injection Interval and the Frio E&F Sand Injection Interval. Only the Case 1 – Sealed Fault A Case is modeled for the Frio D Sand Injection Interval. Future injection is projected at maximum rates through year-end 2020 for both Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162).

The following reservoir parameters were used to conservatively model operational pressure buildup through the projected period (year-end 2020) for both Case 1 and Case 2 models:

- A conservative transmissibility of 320,089 md-ft/cp is used to model the operational pressure buildup in the Frio A/B/C Sand Injection Interval.
- A conservative transmissibility of 315,789 md-ft/cp is used to model the operational pressure buildup in the Frio E&F Sand Injection Interval.

- A conservative transmissibility of 87,719 md-ft/cp is used to model the operational pressure buildup in the Frio D Sand Injection Interval.

- Active offset injection wells are modeled at maximum permitted injection rates for the entire duration of the projected time period.

A discussion of the injection rates used to model the operational plumes follows for each case.

<u>Case 1 – Sealed Fault A Case</u>

Case 1 accounts for the potential no-flow boundaries created by the Renee-Lynchburg Field faults south of the Lyondell Chemical Company Channelview Plant, and the Clinton Dome/Frio B Sand Pinchout west of the plant. The model implicit fault option in the *DuPont Multilayer Pressure Model* accounts for the effects of the Renee-Lynchburg Fault A, and injector "image" wells account for the effects of the Clinton Dome/Frio B Sand Pinchout. Rates for the Clinton Dome injector image wells are identical to those employed for the plume modeling (see Section 2.4.13).

For the Case 1 operational pressure model runs for the Frio A/B/C Sand Injection Interval, the injection history of the Merisol Plant Well 2 (WDW-319), Equistar Plant Well 1 (WDW-36), Atofina's Plant Well 1 (WDW-122) and Plant Well 2 (WDW-230), and Lyondell Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) are modeled. Injection from the Cobra Operating, Texas Northern Railway #6 saltwater disposal well are also included. For the projected period through year-end 2020, Lyondell's maximum requested rate of 700 gpm is successively allocated per well to Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). A maximum cumulative rate of 750 gpm is assigned to Merisol's Plant Well 1 (WDW-147) and Plant Well 2 (WDW-319), a maximum cumulative rate of 350 gpm is assigned to Equistar's Plant Well 1 (WDW-36), a maximum cumulative rate of 300 gpm is assigned to Atofina's Plant Well 1 (WDW-122) and Plant Well 2 (WDW-230), and injection into the Cobra Operating, Texas Northern Railway #6 saltwater disposal well is modeled at its maximum permitted rate of 29.2 gpm. Note that Equistar's Plant Well 1 (WDW-36) has not been used on a sustained basis since 1980 and would only be used in the unlikely event that both Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) were inoperative (the Equistar stream is currently injected into Lyondell's wells, see Section 1), therefore, including this well in the modeling is conservative.

The Case 1 operational pressure model runs for the Frio E&F Sand Injection Interval includes the injection history of the Merisol Plant Well No.1 (WDW-147), Atofina Plant Wells 1 (WDW-122) and 2 (WDW-230), and Equistar Plant Well 1 (WDW-36). Historical injection is allocated at 100 percent in Equistar's Plant Well 1 (WDW-36) into the Frio E&F Sand Injection Interval starting at the beginning of 1977, the year the well was recompleted.

For the projected period through year-end 2020, Lyondell's requested maximum permitted rate of 7000 gpm per well is successively allocated to Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162) [700 gpm cumulative]. Also, to be overly conservative during the projected period, Equistar's maximum permitted injection rate of 350 gpm is allocated to that well, even though that injectate stream is currently injected into Lyondell's wells. A maximum rate of 750 gpm is assigned to the Merisol Plant Well No.1 (WDW-147) and Plant Well 2 (WDW-319) for the projected period through year-end 2020. A maximum cumulative rate of 300 gpm is assigned to Atofina's two wells.

For the Case 1 operational pressure model runs for the Frio D Sand Injection Interval, historical injection is assigned to the Frio D Sand based on the casing leak present in Plant Well 1 (WDW-148) during 1995 and 1996. For the projected period through year-end 2020, Lyondell's maximum requested rate of 425 gpm is successively allocated per well to Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162).

The maximum injection rates in the Case 1 models for both the Frio E&F Sand Injection Interval and the Frio A/B/C Sand Injection Interval are tabulated below.

Facility	Injection Well(s)	Maximum Projected Rate
Merisol	Plant Well 1 (WDW-147) Plant Well 2 (WDW-319)	750 gpm[1]
Cobra	Texas Northern Railway #6	29.2 gpm[2]
Equistar	Plant Well 1 (WDW-36)	350 gpm
Atofina	Plant Well 1 (WDW-122) Plant Well 2 (WDW-230)	300 gpm[1]
Lyondell	Plant Well 1 (WDW-148) Plant Well 2 (WDW-162)	700 gpm

[1] Modeled as cumulative maximum into one well

[2] Modeled for Frio A/B/C Sand Only

The modeled Clinton no-flow boundary in the Case 1 models follows the approximate projection of the -6,200-foot subsurface contour, as identified on the "Top of the Frio E&F Sand Structure Map" (see Appendix 4-9). This contour is projected around the dome, resulting in a curved boundary surface in the Case I models. The modeled boundary conditions in the Case 1 models are shown in Figure 2-15. For the Frio A/B/C Sand Injection Interval, the historical modeled injection area is affected by injection at Equistar (WDW-36), Merisol (WDW-319), and Lyondell (WDW-148 and WDW-162). The projected case model is affected by all of these wells. Four Clinton Dome injection wells were defined for the historical time period and one well is defined for the projected time period in the Frio A/B/C Sand Injection Interval:

Model Period	Time Period	Clinton Injector Well	Location X	Location Y	Flow Proportion
Equistar Only	03/69 - 06/78	D1	-34,000	-5,000	26%
Lyondell & Equistar	07/78 - 9/80	D2	-33,000	-6,200	25.5%
Lyondell Only	10/80 – 12/00	D3	-32,750	-7,200	25.5%
Merisol & Lyondell	01/01 - 12/01	D4	-32,500	-10,000	31.1%
Projected*	01/02 - 12/20	D5	-32,500	-10,500	30.1%

* Projected = Merisol, Lyondell, Equistar, Cobra and Atofina at maximum rates

The *DuPont Basic Plume Model* was used to define the "injection area" of each well (actual well and Clinton Dome Boundary Well). The results for the five time periods in the Frio A/B/C Sand Injection Interval Case 1 Model are shown in Figure 2-16.

For the Case 1 Frio E&F Sand Injection Interval models, the historical modeled injection area is affected by injection at Equistar (WDW-36), Atofina (WDW-122 and WDW-230), and Merisol (WDW-147). The modeled injection area in the projected Case 1 Frio E&F Sand Injection Interval models is affected by injection into the Frio E&F Sand at Lyondell (WDW-148 and WDW-162), as well as, the offset wells. Four Clinton Dome injection wells were defined for the historical and projected time periods in the Frio E&F Sand, as follows:

Model Period	Time Period	Clinton Injector Well	Location X	Location Y	Flow Proportion
Equistar Only	05/77 - 07/79	D1	-34,000	-5,000	26%
Merisol & Equistar	08/79 - 09/80	D2	-33,500	-8,000	24.8%
Merisol Only	10/80 – 12/01	D3	-31,500	-12,500	37.5%
Projected*	01/02 – 12/20	D4	-32,500	-10,500	30.1%

* Projected = Merisol, Lyondell, Atofina, and Equistar at maximum rates

The *DuPont Basic Plume Model* was used to define the "injection area" of each well (actual well and Clinton Dome Boundary Well). The results for the four time periods in the Frio E&F Sand Injection Interval Case 1 Model are shown in Figure 2-17.

Case 2 – Open Fault Case

Case 2 accounts for the possibility that the Renee-Lynchburg Field faults are not barriers to fluid flow and/or pressure buildup (i.e., non-sealing). As such, these model cases include the effects of the Houston Ship Channel area Class I injection facilities, in addition to the facilities considered in the Case 1 models. Potential no-flow boundary effects from the geologic complexities at Clinton Dome, located west of the Lyondell Chemical Company Channelview Plant are, however, included in the Case 2 models. The DuPont model implicit fault option is used to model a potential linear no-flow boundary imposed by Clinton Dome/Frio B Sand Pinchout. The implicit fault is defined by two points in the Case 2 models, located at X_1=-34000. Y_1=-20000., X_2=-26000. Y_2=-6000. This allows for an easier placement of the Clinton Dome Image Wells, as the model correctly places each of the image well locations and injection rates. The modeled boundary in the Case 2 models is shown in Figure 2-18.

The Case 2 operational pressure model runs for the Frio A/B/C Sand Injection Interval and the Frio E&F Sand Injection Interval includes the injection history of the Lyondell wells and the injection history of the nearby plant wells. All of the injection (historic and projected) from the Houston Ship Channel area Class I injection facilities is placed successively into the Frio A/B/C Sand Injection Interval and the Frio E&F Sand Injection Interval, to be conservative. This methodology is conservative, since any real-world flow allocation into adjacent intervals that are also within the completion interval of each well is discounted.

Historical injection is allocated at 100 percent in Equistar's Plant Well 1 (WDW-36) into the Frio A/B/C Sand Injection Interval, since the well has always had the potential to inject into this interval or a portion of this interval. Historical injection is also allocated at 100 percent in Equistar's Plant Well 1 (WDW-36) into the Frio E&F Sand Injection Interval starting at the beginning of 1977, the year the well was recompleted. Historical injection at the Lyondell Channelview Plant is 100 percent allocated to the Frio A/B/C Sand Injection Interval.

The maximum injection rates (permit maximums) used for the offset injection wells in the Case 2 models for both the Frio A/B/C Sand Injection Interval and the Frio E&F Sand Injection Interval are tabulated below:

Facility	Injection Well(s)	Maximum Projected Rate
Merisol	Plant Well 1 (WDW-147) Plant Well 2 (WDW-319)	750 gpm[1]
Equistar	Plant Well 1 (WDW-36)	350 gpm
Atofina	Plant Well 1 (WDW-122) Plant Well 2 (WDW-230)	300 gpm[1]
Lyondell	Plant Well 1 (WDW-148) Plant Well 2 (WDW-162)	700 gpm
GNI	Plant Well 1 (WDW-169) Plant Well 2 (WDW-249)	500 gpm[1]
Vopak	Plant Well 1 (WDW-157)	300 gpm
Hampshire	Plant Well 1 (WDW-222) Plant Well 2 (WDW-222)	300 gpm[1]
Shell	Plant Well 1 (WDW-172) Plant Well 2 (WDW-173)	0 gpm
Cobra Op.	Texas Northern Railway 6	29.2 gpm[2]

[1] Modeled as cumulative maximum into one well

[2] Modeled for Frio A/B/C Sand Only

2.7.1.3.1 DuPont Multilayer Pressure Model Run Files

Pressure contour plots and pressure buildup with time graphs are presented for each of the two model cases (Case 1 and Case 2) for the three injection interval sands (Frio A/B/C Sand Injection Interval, Frio E&F Sand Injection Interval, and Frio D Sand Injection Interval).

Note that model cases were not run for the Frio D Sand Injection Interval for the Case 2 – Open Fault Case models. Extension of the potential line of sand pinch-out shows that the sand is separated from the Houston Ship Channel Area injection well facilities.

The pressure simulation model run files for Case 1 – Sealed Fault A Case are identified below, and are contained in Appendix 2-8, Volumes 16 and 17.

<u>Case 1 – Sealed Fault Case Model Runs</u>

Frio A/B/C Sand Injection Interval	**Model Job File Name**
Plant Well 1 (WDW-148)	abc700_flta_bshale_w1.job
Plant Well 2 (WDW-162)	abc700_flta_bshale_w2.job
Frio E&F Sand Injection Interval	
Plant Well 1 (WDW-148)	ef700_flta_clint_w1.job
Plant Well 2 (WDW-162)	ef700_flta_clint_w2.job
Frio D Sand Injection Interval	
Plant Well 1 (WDW-148)	dsand_flta_dshale_w1.job
Plant Well 2 (WDW-162)	dsand_flta_dshale_w2.job

The pressure simulation model run files for Case 2 – Open Fault Case are identified below, and are contained in Appendix 2-8, Volumes 16 and 17.

Case 2 – Open Fault Case Model Runs

Frio A/B/C Sand Injection Interval	Model Job File Name
Plant Well 1 (WDW-148)	abc700_open_bshale_w1.job
Plant Well 2 (WDW-162)	abc700_open_bshale_w2.job
Frio E&F Sand Injection Interval	
Plant Well 1 (WDW-148)	ef700_open_clint_w1.job
Plant Well 2 (WDW-162)	ef700_open_clint_w2.job

2.7.1.3.2 Case 1 - Operational Pressure Buildup – Frio A/B/C Sand Injection Interval

The Case 1 - Sealed Fault A Case operational pressure buildup run for the Frio A/B/C Sand Injection Interval is generated using a cumulative injection rate of 700 gpm successively into Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162).. The projected period starts at the beginning of 2002 and runs through year-end 2020. Figure 2-71 shows the conservatively predicted incremental pressure increase with lateral distance away from the Lyondell Chemical Company Channelview Plant at year-end 2001, using historical injection and the conservative calibration transmissibility of 320,089 md-ft/cp. Figure 2-72 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using historical injection and the maximum projected cumulative injection rate of 700 gpm into Plant Well 1 (WDW-148) and maximum permitted injection rates at the offset facilities. Figure 2-73 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using historical injection and the maximum projected cumulative injection rate of 700 gpm into Plant Well 2 (WDW-162) and maximum permitted injection rates at the offset facilities.

A graph of the incremental pressure increase with time at Plant Well 1 (WDW-148) is shown in Figure 2-74. Note that the right-hand Y-axis shows the equivalent formation pressure at the model reference depth of 6,884 feet. The maximum modeled incremental pressure increase at Plant Well 1 (WDW-148) at year-end 2020 is 317.5 psi. A graph of the incremental pressure increase with time at Plant Well 2 (WDW-162) is shown in Figure 2-75. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,884 feet. The maximum incremental pressure increase at Plant Well 2 (WDW-162) at year-end 2020 is 317.7 psi. Figures 2-74 and 2-75 also show the model response to a 20-year post-closure time period for the injection wells. Note that pressure recovery is very quick in the first few years following well closure. Annual pressures (incremental and formation pressure at a reference depth of 6,884 feet) with time are presented in Table 2-24.

2.7.1.3.3 Case 1 - Operational Pressure Buildup - Frio E&F Sand Injection Interval

The Case 1 - Sealed Fault A Case operational pressure buildup run for the Frio E&F Sand Injection Interval, is generated using a cumulative future injection rate of 700 gpm successively into Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). The projected period starts at the beginning of 2002 and runs through year-end 2020. Figure 2-76 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using offset historical and the maximum projected cumulative injection rate of 700 gpm into Plant Well 1 (WDW-148) and maximum permitted rates at the offset facilities. Figure 2-77 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using offset historical injection and the maximum projected cumulative injection rate of 700 gpm into Plant Well 2 (WDW-162) and maximum permitted rates at the offset facilities.

A graph of the incremental pressure increase with time at Plant Well 1 (WDW-148) is shown in Figure 2-78. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,625 feet. The maximum incremental pressure increase at Plant Well 1 (WDW-147) at year-end 2020 is 315.0 psi. The incremental pressure increase with time at Plant Well 2 (WDW-162) is shown in Figure 2-79. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,625 feet. The maximum incremental pressure increase at Plant Well 2 (WDW-162) at year-end 2020 is 315.2 psi. Incremental pressure increase at Plant Well 2 (WDW-162) is slightly higher than at Plant Well 1 (WDW-148). Figures 2-78 and 2-79 also show the model response to a 20-year post-closure time period for the injection wells. Note that pressure recovery is very quick in the first few years following well closure.

2.7.1.3.4 Case 1 - Operational Pressure Buildup - Frio D Sand Injection Interval

The Case 1 - Sealed Fault A-A' Case operational pressure buildup run for the Frio D Sand Injection Interval, is generated using a cumulative injection rate of 425 gpm successively into Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). The projected period starts at the beginning of 2002 and runs through year-end 2020. Figure 2-80 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using historical injection and the maximum projected cumulative injection rate of 425 gpm into Plant Well 1 (WDW-148). Figure 2-81 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using historical injection and the maximum projected cumulative injection rate of 425 gpm into Plant Well 2 (WDW-168).

A graph of the incremental pressure increase with time at Plant Well 1 (WDW-148) is shown in Figure 2-82. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,510 feet. The maximum incremental pressure increase at Plant Well 1 (WDW-147) at year-end 2020 is 433.9 psi. The incremental pressure increase with time at Plant Well 2 (WDW-162) is shown in Figure 2-83. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,510 feet. The maximum incremental pressure increase at Plant Well 2 (WDW-162) at year-end 2020 is also 433.9 psi. Figures 2-82 and 2-83 also show the model response to a 30-year post-closure time period for the injection wells. Note that pressure recovery is very quick in the first few years of well closure.

2.7.1.3.5 Case 2 - Operational Pressure Buildup – Frio A/B/C Sand Injection Interval

The Case 2 - Open Fault Case operational pressure buildup run for the Frio A/B/C Sand Injection Interval is generated using a cumulative injection rate of 700 gpm successively into Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). The projected period starts at the beginning of 2002 and runs through year-end 2020. Figure 2-84 shows the conservatively predicted incremental pressure increase with lateral distance away from the Lyondell Chemical Company Channelview Plant at year-end 2001, using historical injection and a transmissivity of 320,089 md-ft/cp. Figure 2-85 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using historical injection and the maximum projected cumulative injection rate of 700 gpm into Plant Well 1 (WDW-148) and maximum permitted rates at the modeled offset facilities. Figure 2-86 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using historical injection and the maximum projected cumulative injection rate of 700 gpm into Plant Well 2 (WDW-162) and maximum permitted rates at the modeled offset facilities.

A graph of the incremental pressure increase with time at Plant Well 1 (WDW-148) is shown in Figure 2-87. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,884 feet. The maximum incremental pressure increase at Plant Well 1 (WDW-147) at year-end 2020 is 335.1 psi. The incremental pressure increase with time at Plant Well 2 (WDW-162) is shown in Figure 2-88. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,884 feet. The maximum incremental pressure increase at Plant Well 2 (WDW-162) at year-end 2020 is 335.9 psi. Incremental pressure increase at Plant Well 2 (WDW-162) is only slightly greater than at Plant Well 1 (WDW-148). Figures 2-87 and 2-88 also show the model response to a 20-year post-closure time period for the injection wells. Note that pressure recovery is very quick in the first few years following well closure.

2.7.1.3.6 Case 2 - Operational Pressure Buildup - Frio E&F Sand Injection Interval

The Case 2 - Open Fault Case operational pressure buildup run for the Frio E&F Sand Injection Interval is generated using a cumulative injection rate of 700 gpm successively into Plant Well 1 (WDW-148) and Plant Well 2 (WDW-162). The projected period starts at the beginning of 2002 and runs through year-end 2020. Figure 2-89 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using offset historical injection and the maximum projected cumulative injection rate of 700 gpm into Plant Well 1 (WDW-148) and maximum permitted rates at the offset facilities. Figure 2-90 shows the conservatively predicted incremental pressure increase with lateral distance away from the Channelview Plant at year-end 2020, using offset historical injection and the maximum projected cumulative injection rate of 700 gpm into Plant Well 2 (WDW-162) and maximum permitted rates at the offset facilities.

A graph of the incremental pressure increase with time at Plant Well 1 (WDW-148) is shown in Figure 2-91. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,625 feet. The maximum incremental pressure increase at Plant Well 1 (WDW-148) at year-end 2020 is 333.4 psi. The incremental pressure increase with time at Plant

Well 2 (WDW-319) is shown in Figure 2-92. Note that the right-hand Y-axis shows the equivalent formation pressure at the reference depth of 6,625 feet. The maximum incremental pressure increase at Plant Well 2 (WDW-162) at year-end 2020 is 334.2 psi. Incremental pressure increase at Plant Well 2 (WDW-162) is the slightly higher than at Plant Well 1 (WDW-148). Figures 2-91 and 2-92 also show the model response to a 20-year post-closure time period for the injection wells. Note that pressure recovery is very quick in the first few years following well closure.

2.7.1.3.7 DuPont Multilayer Pressure Model Summary

The modeled incremental model pressures and the equivalent injection well pressures at the model reference depths for the end of each model-projected year is tabulated in Table 2-24. The tabulation shows that pressure buildup at the injection wells is not excessive and will quickly recover following closure of the injection wells.

2.7.2 Post-Injection Waste Distribution

The post-injection (10,000 year) behaviors of the injection reservoirs are modeled to assess the future factors influencing waste movement and pressure changes. Influencing factors are the ability of the formation to recover its natural pressure gradient (pressure recovery), the steady state of vertical extent, molecular diffusion, and the regional drift of the waste by natural fluid gradients (hydraulic gradients) and buoyancy effects.

2.7.2.1 Pressure Recovery

The *DuPont Multilayer Pressure Model* predicts pressure recovery at the point of injection back towards original formation pressure after cessation of injection. A period of 20 years is used in the post-well closure (starting at year-end 2020) pressure recovery time period. The results from the modeling using maximum injection rates indicates that pressure recovery begins immediately within the injection intervals, with a 60 percent decrease in the formation pressure within the first year after injection ceases. Pressure recovery continues asymptotically, with formation pressure returning to within 38 psi above original pressure after 20 years (Figures 2-74, 2-75, 2-79, 2-80, 2-82, 2-83, 2-87, 2-88, 2-91, and 2-92). These results indicate that the pressure in the injection sands will equilibrate rapidly within the Area of Review and the driving force needed for vertical movement of formation water or waste from an injection interval into an adjacent layer will rapidly dissipate.

2.7.2.2 Vertical Extent

The extent of vertical permeation is driven by the increase in formation pressure during injection. Fluid moves into the base of the overlying aquitard from the injection interval below and compresses some of the native brine immediately above it. This compression raises the pressure within the lower portion of the aquitard, which expands the aquitard pores. Aquitard materials, such as shales, are known to exhibit significant pore expansion. The combined effects of native brine compression and aquitard pore expansion provide the necessary space to store the entering fluid (injection interval brine and injected wastes). After injection has stopped, the driving force for vertical permeation will dissipate (as the pressure buildup in the injection interval dissipates), along with the compressive storage of fluids in the aquitards. The rate of fluid movement into the aquitard layer will decrease to zero, and then reverse, as the aquitard gives fluid back to the injection interval. The vertical permeation distance into the overlying aquitard will approach some final residual (constant) value. Miller et al., (1986) showed that this residual permeation distance is independent of both the compressive properties of the aquitards and the historic variations in waste injection rates. The only aspect of injection history determining the residual permeation distance is the total volume of waste injected at each well.

The long-term vertical permeation submodel evaluates the residual fluid permeation distance within each aquitard layer after an infinite time has passed since injection was discontinued. For sites with more compressive aquitard layers (such as at Lyondell), the maximum permeation occurs during injection and is calculated by the short-term vertical permeation submodel. The equations used in the long-term vertical permeation submodel are detailed in Section 6.2 of Appendix 2-3. After injection at Lyondell has been discontinued, the driving force for vertical permeation will dissipate and the extent of vertical permeation will decrease to some final residual value. This residual value will remain constant past the 10,000-year regulatory time frame. Using the maximum injection rate of 425 gpm in the Frio D Sand as a worst-case scenario (shallowest injection interval sand), the residual vertical permeation value for the injected waste and formation brine in the aquiclude layer overlying the Frio D Sand will not exceed 2.32 feet (Figure 2-70 and Appendix 2-9, Volume 17) from a maximum upward permeation value of 14 feet at the end of active injection (see Section 2.7.1.2).

Molecular diffusion is, by far, the dominant vertical transport mechanism for contaminant species over the 10,000 year time period. Critical parameters for the constituents of concern are shown in Table 2-13. The dimensionless vertical distance "z" for each constituent's specific concentration reduction factor in Table 2-13 is determined via a look-up function in Microsoft

EXCEL® to the error function of 1 minus the concentration reduction factor. This relationship is shown graphically in Figures 2 and 3 of Appendix 2-4. However, the Microsoft EXCEL® look-up function is computationally more accurate and allows for calculations beyond a concentration reduction factor of 10^{-7}. Molecular diffusion distances for the constituents of concern over the 10,000-year regulatory time frame are been calculated using an upper bound shale porosity of 21 percent, which corresponds to a geometric correction factor (GCF) of 0.0441 (GCF = ϕ^2) for the shales overlying the Frio D Sand. Diffusion distances are shown in Table 2-13 for all of the constituents of concern.

The following sample calculation is provided to illustrate the employed methodology:

Example Problem

Benzene is diffusing into the shale aquitard layer overlying the Frio D Sand injection interval. From health-based standards and its maximum wellhead concentration, it is determined that the contaminant concentration would have to be reduced by a factor of 4.72×10^{-5} in order to be considered non-hazardous. The diffusion coefficient for the species in free aqueous solution, at a temperature corresponding to the depth of injection, has been determined, using the method of Hayduk and Laudie (1974), to be 2.3×10^{-5} cm^2/sec. The porosity of the shale is 21 percent.

Example Solution

From Figure 3, the dimensionless vertical diffusion distance required to produce a relative concentration of 1.0×10^{-6} is found to be 3.458:

$$\frac{z}{2\sqrt{D^* t}} = 3.458$$

This translates into an actual (dimensional) vertical diffusion distance of:

$$z = 6.916^* \sqrt{D^* t}$$

For shales overlying the Frio D Sand, a conservative estimate of the geometric correction factor G for contaminant diffusion through the water-saturated porous matrix is given by the relationship $G = \phi^2$. In the present case of $\phi = 0.21$, this results in an upper bound of

0.0441 for G. Since the diffusivity in free solution is 2.3×10^{-5} cm^2/sec, the effective diffusion coefficient in the porous shale medium is:

$$D^* \leq 2.3 \times 10^{-5} \times (0.0441) = 1.01 \times 10^{-6}\ cm^2/sec$$

Substituting this value for D* into the equation given above for z, and using a value of 10,000 years (= 3.16×10^{11} sec) for t yields:

$$z \leq 6.916\sqrt{\left(1.01\times10^{-6}\right)\left(3.16\times10^{11}\right)}$$

$$\leq 3{,}907.1cm$$

$$\leq 128\ \text{ft}$$

Adding a 5 percent uncertainty due to the 10 percent uncertainty in the free water diffusivity, the diffusion distance into the overlying aquitard layer after 10,000 years is predicted to be no greater than 135 feet (128 feet + 0.05 * 128 feet).

The overall maximum (conservative) vertical incursion of waste into the aquitards overlying the Frio D injection sand is obtained by adding together the results from the molecular diffusion calculations (most mobile molecule thallium = 189 feet) and the vertical permeation value from year-end 2020 (using maximum injection rates = 14 feet). The predicted overall vertical waste incursion is predicted to be less than 203 feet for the furthest traveling (most mobile) constituent (thallium). A minimum of 800 feet of net shale (out of a total of 1,350 feet of sand and shale) is present between the top of the Frio D injection sand and the top of the permitted injection zone. Based on these values, it is demonstrated that the injected waste will be contained within the injection zone and not migrate vertically upward out of the injection zone within 10,000 years, even under the revised conditions requested in this 2000 HWDIR Exemption Petition Reissuance.

2.7.2.3 Horizontal Extent

During injection, the movement of waste within the injection reservoir is dominated by the volumetric growth of the waste plume. Once injection has been discontinued, the horizontal rate of waste movement is dependent on the natural regional hydraulic gradient of the injection reservoir, density driven drift and hydrodynamic dispersion. The long-term horizontal movement of the waste plume is predicted in this 2000 HWDIR Exemption Petition Reissuance using the *DuPont 10,000-Year Waste Plume Model.*

During injection, the movement of waste within the injection reservoir is dominated by the volumetric growth of the waste plume. Once injection has been discontinued, the horizontal rate of waste movement is dependent on the natural regional hydraulic gradient of the injection reservoir, density driven drift and hydrodynamic dispersion. The long-term horizontal movement of the waste plume is predicted using the *DuPont 10,000-Year Waste Plume Model.*

Induced pressure gradients from man-made activities (injection, oil and gas extraction, etc.) are not expected to have a major effect on lateral plume movement during the early part of the 10,000-year time period for the Lyondell Chemical Company, Channelview site. Injection into the offset injection wells has already been incorporated into the petition modeling and any subsequent pressure effects from these wells will rapidly dissipate after well closure. Oil and gas production in the regional area near the plant site is primarily from the stratigraphically and structurally deeper Vicksburg and Yegua Formations, which are separated from the Frio injection reservoirs by thick shale layers. Production from these formations will have no effect on the 10,000-year plume movement.

Many of the studies for flow rates in deep saline aquifers come from the search for nuclear waste isolation sites. These studies show sluggish circulation to nearly static conditions in the deep subsurface (see Appendix 2-6, Volume 5 - Groundwater Flow in Deep Saline Aquifers). Original formation pressure gradient data for the Frio Formation in the Channelview area substantiates the lack of a large hydraulic gradient for the basal Frio sands. Original formation pressure gradients from Lyondell Chemical Company, Plant Well 1 (WDW-148), from Equistar Plant Well 1 (WDW-36), located approximately 16,500 feet northwest, and from the Merisol Plant Well 1 (WDW-147), located approximately 33,000 feet southwest, are nearly identical ($\pm$ 0.001 psi/feet).

Lyondell Chemical Company presents literature data in the Petition (Appendix 2-6, Volume 5 - Groundwater Flow in Deep Saline Aquifers) that indicates that background velocities in the deep subsurface are generally less than 1.0 feet/year. To provide a greater margin of safety, Lyondell Chemical Company is making a very conservative determination that 1.62 feet/year is the maximum expected background velocity in the lower Frio. Lyondell Chemical Company believes that the background velocity of 1.62 feet/year is very conservative. Since lateral facies changes, which result in sand pinch-outs, are known to occur in the direction of the recharge area, the background hydraulic gradient is greatly exaggerated in the Petition. These facies changes were discounted in the original conservative determination. Data from Baker (1979) Stratigraphic and Hydrogeologic Framework of Part of the Coastal Plain of Texas, Texas Department of Water Resources (Report 236), indicates that the Frio Formation is the down dip equivalent of the Catahoula Confining System. The attached Cross Section (C - C') (Figure 2-93), from Baker (1979), shows that the sandy lower Frio section near the plant site grades into the shaly Catahoula section towards the outcrop area (potential recharge area). Corroborating data from Galloway, et al. (1982) Frio Formation of the Texas Gulf Coast, Bureau of Economic Geology (Report 122), supports lateral sand pinch-outs between the Lyondell Chemical Company facility and the potential recharge area, as sands of the Houston Delta System (Lyondell Chemical Company injection intervals) grade up dip into sands of the Chita/Corrigan Fluvial System. Sand Percentage maps of the lower Frio section show a marked decrease in sand content approximately 15 to 25 miles west and northwest of the Lyondell Chemical Company facility. It is in this area that the sand pinch-outs that restrict flow would be expected to occur.

The second component influencing plume drift over 10,000 years is density driven flow. At the present time, the waste injected by Lyondell Chemical Company is, on average, less dense than the native formation brine in the Frio injection reservoirs. Therefore, the primary density driven flow component is directed up-dip, opposite to the flow induced by the natural regional gradient.

The following analytical relationship (without dispersion) is used to determine the initial drift velocity due to density differences between the effluent plume and formation fluid (assumes isothermal conditions):

$$D_d = 9.49E^{-2}\left(\frac{(\rho_e - \rho_f)k\beta}{(\varphi\mu)}\right)$$

Where:

D_d = density drift (ft/yr)
ρ_f = density of the native formation fluid (gm/cm^3)
ρ_e = density of the effluent (gm/cm^3)
k = permeability (darcies)
β = formation dip rate (ft/mile)
φ = formation porosity (fractional)
μ = fluid viscosity (centipoise)

The equation, above, is the dimensionally solved form of the last equation contained in Section 13.B of Appendix 2-5. Note that it is the difference in density (ρ_e - ρ_f) that is critical to the calculation, therefore, relative values at the same constant temperature can be used as inputs.

Hydrodynamic dispersion will act to reduce the density-driven contribution to the overall velocities in the *DuPont 10,000-Year Waste Plume Model.* The dispersive mixing process will result in dilution of the waste plume, which will simultaneously reduce both the concentrations of the hazardous constituents in the plume and the density differences between the waste and the formation fluid. The magnitude of the density driven drift component is very sensitive to the dip rate of the geological strata. All other inputs being equal, a doubling of the dip rate will double the magnitude of the initial density driven drift component. In steeply dipping strata, a buoyant waste plume may drift up-dip, against the natural background regional flow, over the 10,000-year time frame. To be overly conservative in the present analysis of the Low Specific Gravity Plume, it is assumed that there is no down-dip background flow component. This conservative assumption will result in a significant overprediction of the distance of plume transport over the 10,000-year regulatory period.

It can confidently be stated that at the Lyondell Chemical Company site, injected effluent plumes that are denser than the native formation brines present no environmental danger or risk to human health or the environment since they have no buoyant vertical driving force that would result in plume movement to shallower depths (i.e., they are confined between aquiclude layers). Due to density effects, modeling results have shown that high density effluent plumes, like those injected at the Lyondell Chemical Company site, will in fact tend to "sink", moving deeper into the subsurface, thereby increasing the amount of vertical separation of the plume from the environment. The area immediately downdip of the site consists of uninterrupted homoclinal dipping strata. This area has been penetrated by several oil and gas test wells, which have found no hydrocarbons. It is unlikely that any additional testing will occur in this area. Therefore, it is appropriate to evaluate the high specific gravity plume over a shorter time span. A conservative time period of 200 years is chosen for the evaluation period. Formation pressures will have decayed and no Cone of Influence is present well within this 200 year time period.

The DuPont 10,000 Year Waste Plume Model is a two-dimensional model simulation of flow and plume transport (Section 2.3.4 and Appendix 2-5). Note that the third dimension (formation or plume thickness) is inherently considered in the DuPont 10,000 Year Waste Plume Model in the assignment of the nominal plume radius input parameter. As shown in equation 1-a (the governing transport equation) in Appendix 2-5, the rate ~~of plume transport~~ DuPont 10,000 Year

Waste Plume Model is directly proportional to the input mobility (k/μ) ratio. Mobilities are conservatively set in the models (see Tables 2-25 through 2-27). In the long-term modeling of the Frio A/B/C Sand, the DuPont 10,000 Year Waste Plume Model considers a mobility (k/μ) ratio of 4,629.63 md/cp. Using a conservative net thickness of 160 feet for the Frio A/B/C Sand falloff and interference tests (Table 2-3) indicates a mobility (k/μ) ratio of less than 4,000 md/cp, which is significantly less than the modeled value (note that using a greater sand interval thickness approaching the gross sand thickness value of 195 feet would result in an even lower calculated mobility ratio of 3,282 md/cp from the tests). The mobility ratio modeled in the long-term transport demonstration for the Frio A/B/C Sand Injection Interval exceeds that determined from annual falloff test. Therefore, all things being equal, the modeled plume transport will exceed actual long-term plume transport in the interval.

In the long-term modeling of the Frio E&F Sand, the DuPont 10,000 Year Waste Plume Model considers a mobility (k/μ) ratio of 6,481.48 md/cp. The initial falloff test in the recompleted Plant Well 2 (WDW-162) showed a transmissibility (kh/μ) product of 569,038.24 md-ft/cp. Using a conservative net thickness of 155 feet for the Frio E&F Sand this falloff test indicates a mobility (k/μ) ratio of 3,671.2 md/cp, which is significantly less than the modeled value (note that using a greater sand interval thickness approaching the gross thickness value of 215 feet would result in an even lower calculated mobility ratio of 2,646.7 md/cp from the test). The mobility ratio modeled in the long-term transport demonstration for the Frio E&F Sand Injection Interval greatly exceeds that determined from annual falloff test. Therefore, all things being equal, the modeled plume transport will exceed actual long-term plume transport.

2.7.2.3.1 Horizontal Extent – Low Specific Gravity Plume

For the Low Specific Gravity Plume, in order to be conservative, a regional flow is set to zero in the basal Frio Sands. Therefore, predictions of plume movement are influenced only by the specific gravity contrast between the effluent plume and the formation fluid, and the dip rate of the geologic strata. In order to be overly conservative, the specific gravity of the modeled Low Specific Gravity Plume (three month weighted average) is assumed to be entirely at a specific gravity value of 1.028 at 60° F in the Frio Injection Interval Sands. Model inputs are shown in Tables 2-25 through 2-27 for the three injection interval sands. The model results for the Low Specific Gravity Plumes in each injection interval at 2,500-year time steps are shown in Figure 2-94 through 2-96. Results are presented in terms of relative concentration (i.e., the concentration of a species scaled to its value in the waste stream) as a function of lateral position. Relative concentration contours are provided for a factor of 10. Note that the relative concentration required to meet health-based standards is 10^{-6}. The *DuPont 10,000-Year Waste Plume Model* results are also shown on the key maps in Section 3.0 and Section 4.0 for the 10^{-6} contour. Model runs are summarized below:

Low Specific Gravity Model Runs		Appendix 1-10, Volumes 18, 19 and 20
Frio A/B/C Sand	Frioabc_ld2002.job	
Frio E&F Sand	Frioef_ld2002.job	
Frio D Sand	friod_ld2002.job	

The model results for the Low Specific Gravity Plume in the Frio sands, based on the conservative model inputs, indicate that the plumes will extend to the north-northwest beyond the 2.5-mile radius Area of Review (Figures 2-94 through 2-96). The leading edge of the farthest moving plume (Frio A/B/C Sand Injection Interval) is located no more than 70,000 feet from the injection wells after 10,000 years (Figure 2-94). Width of the plume at its widest point (located at the modeled change in slope break from 168 feet per mile to 65 feet per mile, located approximately 40,000 to 60,000 feet up structure from the Channelview Plant) is approximately 25,000 feet. The leading edge of the Frio E&F Sand Injection Interval Low Specific Gravity Plume is located no more than 59,000 feet up structure from the Channelview Plant injection wells (Figure 2-95). Width of the plume at its widest point (located at the modeled change in slope break from 90 feet per mile to 35 feet per mile, located approximately 50,000 to 62,000 feet up structure from the Channelview Plant) is approximately 16,000 feet. The leading edge of the Frio D Sand Injection Interval Low Specific Gravity Plume is located no more than 67,000 feet up structure from the Channelview Plant injection wells (Figure 2-96). Width of the plume at its widest point (located at the modeled change in slope break from 199 feet per mile to 60 feet per mile, located approximately 38,000 to 60,000 feet up structure from the Channelview Plant) is approximately 15,000 feet. Note that the perimeter of the 10^{-6} concentration reduction factor in the Frio A/B/C Sand Injection Interval exceeds that areal size and extent of the plumes in the either the Frio E&F Sand Injection Interval and the Frio D Sand Injection Interval.

2.7.2.3.2 Horizontal Extent – High Specific Gravity Plume

For the High Specific Gravity Plume, in order to be conservative, an upper bound regional background flow of 1.62 ft/yr in the basal Frio Sands is used as an input into the model (Tables 2-25 through 2-27). Therefore, the prediction of plume movement is influenced not only by the specific gravity contrast between the dense effluent plume and the formation fluid, but also by the background regional flow. In order to be overly conservative, the average specific gravity of the modeled High Specific Gravity Plume (three month weighted average) is assumed to be 1.100 at 60 °F in the Frio A/B/C Sand Injection Interval, the Frio E&F Sand Injection Interval, and the Frio D Sand Injection Interval. Model inputs are shown in Tables 2-25 through 2-27 for the three injection interval sands. The model results for the High Specific Gravity Plume after 200 years are shown in Figures 2-97 through 2-99. Results are presented in terms of relative concentration (i.e., the concentration of a species scaled to its value in the waste stream) as a function of lateral position. Relative concentration contours are provided for a factor of 10. Note that the relative concentration required to meet health based standards is 10^{-6}. The *DuPont 10,000-Year Waste Plume Model* results are also shown on the key maps in Section 3 and Section 4 for the 10^{-6} contour. Model runs are summarized below:

High Specific Gravity Model Runs		Appendix 2-11, Volume 20 and 21
Frio A/B/C Sand	Frioabc_hd2002.job	
Frio E&F Sand	Frioef_hd2002.job	
Frio D Sand	Friod_hd2002.job	

The model results for the High Specific Gravity Plume in the basal Frio Injection Interval Sands, based on the conservative model inputs, indicate that the plume is contained within the 2.5-mile radius Area of Review, east-southeast of the plant (Figures 2-98 and 2-99) for the Frio E&F Sand Injection Interval and the Frio D Sand Injection Interval. However, a small portion of the High Specific Gravity Plume will extend beyond the Area of Review Boundary for the Frio A/B/C Sand Injection Interval, based on the conservative location of the Operational Plume at year-end 2020. The leading edge of this High Specific Gravity Plume is modeled to move no more than 1,500 feet during the 200-year evaluation period [i.e., the leading edge of the plume (1.0E-06 concentration reduction factor)] will move approximately 1,500 feet downdip of its year-end 2020 position.

2.7.2.3.3 Long-term Plume Sensitivity Runs

Several sensitivity runs to the long-term plume models were made to ensure that the model predictions are conservative. These include a low specific gravity sensitivity to the Top of the Frio C Sand Structure, a low specific gravity dispersivity sensitivity to the Frio A/B/C Sand

Injection Interval, and a high specific gravity dispersivity sensitivity to the Frio A/B/C Sand Injection Interval. The Frio A/B/C Sand Injection Interval plume runs are used in the dispersivity sensitivity modeling because they result in the larges base case plume perimeters at all times (see Figures 2-94 through 99). The model sensitivity runs are detailed below.

Low Specific Gravity Sensitivity Model – Top of Frio C Sand Model

As a sensitivity to the Top of the Frio A Sand used in the Frio A/B/C Sand Injection Interval Low Specific Gravity Plume model, a sensitivity to structure is made using the conservative assumption that all of the historic and future injection is contained in the Frio C Sand. Note that the Frio C Sand (Figure 2-12) has a slightly different structural configuration than does the Frio A Sand (Figure 2-11). Therefore, the .LCL was modified for the specific dip rate for the Frio C Sand (see Section 2.4.12.1). Additionally, the plume radius used in the sensitivity is the base case nominal plume for the Frio A/B/C Sand (see Figure 2-34) since the Frio C sand maintains an average thickness of 50 feet in the updip direction. The model run for the sensitivity case is identified below:

Low Specific Gravity Model Run Frio A/B/C Sand – Dip Sensitivity	Frioabc_ld2002_cdip.job	Appendix 2-11, Volume 19

Results of the model sensitivity are shown in Figure 2-100. The extent of plume transport is less (by approximately one-half mile) than in the base case model run (Figure 2-94). Additionally, the width of the plume at its widest point (located at the modeled change in slope break from 153 feet per mile to 68 feet per mile, located approximately 40,000 to 55,000 feet up structure from the Channelview Plant) is less than for the base case model run (Figure 2-94).

Low Specific Gravity Sensitivity Model – Frio A/B/C Sand Dispersivity

As a sensitivity to the employed dispersivity of 93 feet used in the Low Specific Gravity Plume runs, an upper-bound longitudinal dispersivity of 300 feet is considered in the Dispersivity Sensitivity Case Model. In general, lower dispersivity results in a more compact plume, which leads to greater distance of transport. The sensitivity is based on the upper-end dispersivity calculated for 70,000 feet of potential movement using a 1:1:1 weighting factor (Xu and

Eckstein, 1995). All other parameters in the Frio A/B/C Sand Injection Interval Low Specific Gravity Plume run remain the same. The model run for the sensitivity case is identified below:

<u>Low Specific Gravity Model Run</u> Frio A/B/C Sand – Dispersivity Sensitivity	Frioabc_disp_ld2002.job	Appendix 2-11, Volume 18

Results of the model sensitivity are shown in Figure 2-101. As expected, the extent of plume transport is less (by approximately one mile) than in the base case model run (Figure 2-94). However, the larger dispersivity results in a wider plume at all time periods. Width of the plume at its widest point (located at the modeled change in slope break from 168 feet per mile to 65 feet per mile, located approximately 40,000 to 60,000 feet up structure from the Channelview Plant) is approximately 31,000 feet.

<u>High Specific Gravity Sensitivity Model – Frio A/B/C Sand Dispersivity</u>

As a sensitivity to the employed dispersivity of 55 feet used in the High Specific Gravity Plume runs, an upper-bound longitudinal dispersivity of 160 feet is considered in the Dispersivity Sensitivity Case Model. In general, lower dispersivity results in a more compact plume, which leads to greater distance of transport. The sensitivity is based on the upper-end dispersivity calculated for 10,000 feet of potential movement using a 1:1:1 weighting factor (Xu and Eckstein, 1995). All other parameters in the Frio A/B/C Sand Injection Interval High Specific Gravity Plume run remain the same. The model run for the sensitivity case is identified below:

<u>High Specific Gravity Model Run</u> Frio A/B/C Sand – Dispersivity Sensitivity	Frioabc_disp_hd2002.job	Appendix 2-11, Volume 21

Results of the model sensitivity are shown in Figure 2-102. In this case, the extent of plume transport is slightly greater than in the base case model run (Figure 2-97) due to the short time frame of the model run and the larger initial disperse plume used in the sensitivity (i.e., the outer perimeter of the initial disperse plume, using a dispersivity of 160 exceeds the total plume movement of the base case High Specific Gravity Plume even including a 200 year evaluation period). Downdip extent of the disperse plume sensitivity is approximately 11,300 feet from the origin (approximately 1,500 feet of movement for the leading edge of the plume from its initial position to its position after the 200 year evaluation period).

2.7.2.3.4 Horizontal Extent – Composite Plume

The perimeter of the composite long-term plume is shown on Figure 2-103. The Figure shows the outermost perimeter of the Frio A/B/C Sand Injection Interval at year-end 2020 using the conservative Multiplying Factor of 3.8 (Operational Plume). To be conservative in the evaluation, the distance of movement of the Frio A/B/C Sand Injection Interval High Specific Gravity – Dispersivity Sensitivity Plume (1,500 feet down dip) is directly added to the perimeter of the Frio A/B/C Sand Injection Interval Operational Plume at yearend 2020. If measured from the point of injection at Lyondell's wells, the perimeter of the of the High Specific Gravity – Dispersivity Sensitivity Plume (1,500 feet down dip) as shown in Figure 2-102 would **not** extend beyond the perimeter of the Frio A/B/C Sand Injection Interval Operational Plume shown on Figure 2-103.

Long-term modeling indicates that a "swatch" of Low Specific Gravity Plume will emerge from the 2.5-mile radius Area of Review in the up-dip direction (west and then northwest) over the 10,000-year regulatory evaluation period. The perimeter of the Frio A/B/C Sand Injection Interval Low Specific Gravity – Dispersivity Sensitivity Plume (Figure 2-101) is shown on the composite long-term plume is shown on Figure 2-103. Additionally, the perimeter of the Frio A/B/C Sand Injection Interval Low Specific Gravity Plume (Figure 2-94) that extends beyond the Frio A/B/C Sand Injection Interval Low Specific Gravity – Dispersivity Sensitivity Plume is shown on the composite long-term plume is shown on Figure 2-103. In the up-dip direction, this swatch will be approximately 31,000 feet wide (at its widest point) and will extend 70,000 from the injection wells. Comparison with the local geology shows that none of the waste will interface with a USDW or with a known point of discharge over the regulatory evaluation period (see Section 4.0).

2.8 Sensitivity Analysis – Operational Modeling

Every effort has been made to use conservative inputs for the models, so the modeling outputs will present reasonable, conservative upper bounds to the actual case as it exists in the subsurface at the Lyondell Chemical Company, Channelview Plant. The models can be considered to be idealized simulators of the subsurface in that they accept only one value per parameter for each layer in the model. In the subsurface, the actual parameter values in each layer either vary over a natural range or the certainty in the value is only known within a range. By selecting the conservative end of the value or certainty range for each model, contaminant transport and pressure buildup has been over estimated in the model results (see Section 2.5). The following paragraphs summarize general statements about model sensitivity.

Decreasing sand thickness increases the following: upward permeation, pressure buildup at the injection well, pressure buildup at the Area of Review boundary and waste plume extent. The results for increased thickness are decreases in upward permeation, pressure buildup and waste plume extent. The model is more sensitive to decreases than to increases in sand thickness.

The results of the Flow and Containment Model are, to a large degree, not particularly sensitive to the values employed for the sand layer porosities. Only the results from the lateral waste transport model, the Basic Plume Model, shows mild sensitivities to sand body porosities. The predicted lateral extent of a waste plume during injection varies roughly in inverse proportion to the square root of sand porosity. Only variations in thickness and porosity have an effect on the extent of the waste plume.

Decreasing permeability in the model increases upward permeation and pressure buildup, while increasing permeability has the opposite effect on the model. The model is more sensitive to decreases in sand permeability than to increases in sand permeability.

When viscosity is varied over a one-tenth centipoise range, the model results are approximately equally sensitive to both increases and decreases in viscosity. The model is more sensitive to increases in sand compressibility than to decreases.

Upward permeation and pressure buildup respond independently to changes in the confining shale permeability, the model being more sensitive to increases in shale permeability than to decreases. When shale compressibility is varied by one order of magnitude, only upward permeation is effected. The models are more sensitive to increases in confining shale compressibility and permeability than to reduction in these parameters.

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2.9 Summary of Results

The Flow and Containment modeling analysis for the Lyondell Chemical Company, Channelview Plant, conservatively modeled the injection of waste fluids into subsurface formations under modified conditions. Geologic parameters are validated through the overmatching of model pressure predictions with formation shut-in pressures and flowing downhole pressures in the injection reservoirs. The Flow and Containment modeling package modeled two time frames under the modified conditions:

1) The end of 2020 (near future, based on maximum injection data).

2) A 10,000-year post-closure period.

Modeling results based on the maximum projected injection rates through the end of 2020 are:

1) The maximum horizontal extent of the waste is projected to occur in the Frio A/B/C Sand Injection Interval. The injected waste is generally contained within the Area of Review, except for a small portion that extends to the northeast and east.

2) There is no vertical permeation of fluids out of the Frio and Vicksburg Injection Zone. The maximum amount of vertical permeation of fluids into the aquiclude immediately overlying the Frio D Sand will not exceed 14 feet.

3) The maximum pressure increase at the Area of Review boundary will not exceed 238 psi in the Frio A/B/C Sand Injection Interval at the maximum cumulative injection rate (700 gpm), and will not exceed 218 psi in the Frio E&F Sand Injection Interval at a cumulative injection rate of 700 gpm. At a cumulative injection rate of 425 gpm into the Frio D Sand, the pressure at the Area of Review boundary will not exceed 232 psi.

Modeling on a 10,000 year time frame shows that within the Area of Review, the pressure build-up due to injection rapidly decreases, indicating that there will no longer be a Cone of Influence within one year post-closure. As the formation pressure decreases, vertical permeation will also decrease and the residual vertical permeation value for the injected waste and formation brine in the aquiclude layer overlying the Frio D Sand will not exceed 1.5 feet. Total vertical extent of the waste (most mobile constituent) will not exceed 203 feet (maximum diffusion and vertical permeation) of the overlying 800 feet of shale above the Frio D Sand within the injection zone.

Drift of the High Specific Gravity Plume in hazardous concentrations over a 200-year evaluation time period will extend approximately 1,500 feet down dip of location of the operational plume perimeter. Drift of the Low Specific Gravity Plume will not exceed a distance of 70,000 feet to the northwest of the site over the 10,000-year regulatory evaluation period. Therefore, it can confidently be stated that to a reasonable degree of certainty, there will be no migration of hazardous constituents from the injection zone for as long as the waste remains hazardous, either vertically upward out of the injection zone or laterally within the injection zone to a point of discharge or interface with a USDW.